THE EDWARDS LIMESTONE IN THE BALCONES FAULT ZONE, SOUTH-CENTRAL TEXAS

APPROVED BY SUPERVISORY COMMITTEE:

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THE EDWARDS LIMESTONE IN THE BALCONES FAULT ZONE, SOUTH-CENTRAL TEXAS

by

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DISSERTATION

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When you have eliminated all which is impossible,
then whatever remains, however improbable,
must be the truth.

Sir Arthur Conan Doyle
in "The Complete Sherlock Holmes"

You might compare climbing El Capitan with writing a
Ph.D. dissertation. It's essentially meaningless.

Dean Caldwell (1st man to climb sheer face
of El Capitan in Yosemite)
in "Sports Illustrated" May 3, 1971

Most men will not swim before they are able to. Novalis
(nom de plume for Friedrich von Hardenberg,
student of Werner at Freiberg)

Naturally they won't swim! They are born for the solid
earth, not for the water. And naturally they won't
think. They are made for life, not for thought.
Yes, and he who thinks, what's more, he who makes
thought his business, he may go far in it, but he
has bartered the solid earth for the water all the
same, and one day he will drown.

Herman Hesse
in "Steppenwolf"

Acknowledgements

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I am also indebted to my permanent committee members, Dr. William L. Fisher and Dr. L. Jan Turk, for their helpful suggestions and criticisms.

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Certain aspects of the problem were individually discussed with Joe Pearson, Ted Small, Dick Reeves and Paul Rettman in the San Antonio office of the U. S. Geological Survey.

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The Edwards Limestone (Albian) is a mosaic of shallow water, back-reef, carbonate lithofacies averaging about 450 feet thick, that have been dolomitized, chertified and dedolomitized.

Intermittent subaerial exposure during and shortly after deposition of the Edwards resulted in secondary solution-enlargement of some primary voids. Slow upwarping of the northwestern margin of the subsiding Gulf of Mexico basin elevated the Edwards Group above sea level late in the Cretaceous. Down-to-the-coast, en echelon, normal faulting along the Balcones system during the Early Miocene accentuated the topographic position of the Edwards above sea level. Rejuvenated Gulfward flowing streams cut into the upthrown fault block and exposed the top of the Edwards Limestone in deep canyon bottoms. This created discharge sites that initiated a continuously circulating ground-water system in the Edwards Limestone. Early porosity systems have increased in size through the self-ramifying cavern solution process that occurs in carbonate rocks. The resultant cavern system presently supplies water for

most of south-central Texas.

Some faults have acted as barriers which have caused a preferential channelization of ground-water flow into separate but parallel systems. Ground water moving toward low discharge points, e.g. Comal Springs, has created widespread cavern systems.

Removal of much Upper Cretaceous overburden during the Neogene and declines of the water table due to stream incision have changed the Edwards Group in the eastern Edwards plateau into a lower yield unconfined aquifer. The prolific artesian aquifer system beneath the western margin of the Gulf Coastal plain is still increasing in size.

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INTRODUCTION

The Edwards Limestone of south-central Texas is a cavernous container holding tremendous quantities of fresh water. There are a number of only partially answered questions about this aquifer system, e.g.

How was the porosity created?

How was the sequential development of porosity related to the geologic history of the region?

What is the relationship between porosity and different facies within the Edwards?

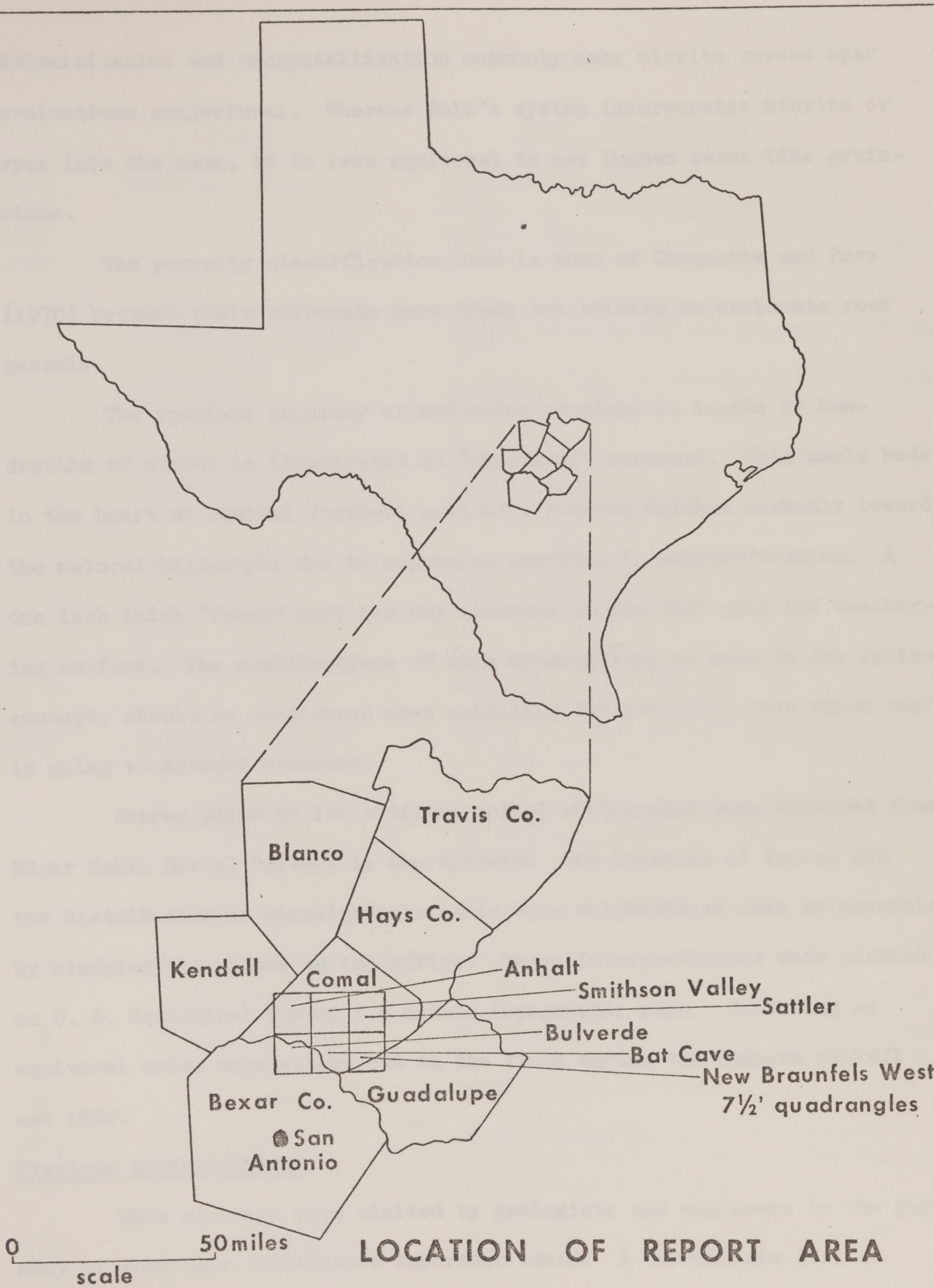
Improved answers to these questions have been sought by looking closely at some of the Edwards Limestone exposed in the Balcones fault zone.

Area investigated

Geology was mapped on the Sattler, New Braunfels West, Smithson Valley, and Bulverde 7.5 minute quadrangles in Comal and Bexar Counties (see figure 1 and/or map packet inside rear cover). Measured sections were described on the outcrop in Travis, Blanco, Kendall, Comal and Bexar Counties (see individual measured sections in appendix for precise locations). Cores from Comal and Bexar Counties were described (see appendix).

Methods

The terminology used to describe these carbonate rocks lithologically is from the classifications of Folk (1962) and Dunham (1962). The spectral subdivision of Folk allows more specific descriptions, especially where differing energy regimes have acted on diverse allochems in the presence of a source of micrite. But usually the grains in the Edwards are skeletal debris with supplemental intraclasts, and the extensive



LOCATION OF REPORT AREA

Figure 1

dolomitization and recrystallization commonly make micrite versus spar evaluations conjectural. Whereas Folk's system incorporates micrite or spar into the name, it is less equivocal to use Dunham terms like grainstone.

The porosity classification used is that of Choquette and Pray (1970) because their carbonate pore types are related to carbonate rock genesis.

The spurious accuracy of measuring sections to tenths or hundredths of a foot is illustrated in "synclinal" roadcuts. Thin marly beds in the heart or central freshest part of a roadcut thicken markedly toward the natural hillslopes due to expansion involved in calichification. A one inch thick "fresh" marl bed may increase to one foot near the weathering surface. The ramifications of this observation, as well as the facies concept, should be considered when selecting the precision with which one is going to measure sections.

Stereo pairs of low altitude aerial photographs were obtained from Edgar Tobin Aerial Surveys in San Antonio. The location of faults and the distribution of stratigraphic units were delimited as well as possible by studying the photos in the office. These interpretations were plotted on U. S. Geological Survey 7.5 minute topographic maps. Confusing or equivocal areas were walked out in the field during the summers of 1971 and 1972.

Previous investigations

This area has been visited by geologists and engineers in the past; many of whom have contributed important ideas. A chronologic list of these investigations is given in Table 1.

TABLE 1. PREVIOUS INVESTIGATIONS

YEAR	OBSERVER	DESCRIPTION OF WORK
1846 1848 1849 1852	Ferdinand Römer	Extensive early study of Cretaceous strata and fossils in German-settled central Texas
1898	Robert T. Hill & T. Wayland Vaughan	Geology, geography and occurrence of ground water in eastern Edwards plateau
1924	W.S. Adkins	Georgetown Fm. in McClennan Co. divided into seven members
1925-1935	F.L. Whitney & students	Geologic mapping in Comal and Hays Co. (edited by Keith Young in 1956 for Bur. Econ. Geology)
1930	Gus K. Eifler	Study of Edwards Limestone in central Texas with emphasis on Travis Co. and paleontology
1930	Stewart W. Horne	Measured sections of Walnut Fm. in Comal Co. and northward
1932	Kenneth S. Cronin	Report on Edwards-Georgetown contact in Comal and Hays Co.
1932	Lon Cartwright Jr.	Topography of pre-Cretaceous surface and regional structure of Edwards plateau
1933	W.S. Adkins	Regional description of Texas Cretaceous
1936	Penn Livingston, *et al*.	Water resources of the Edwards Limestone in the San Antonio area
1941	William C. Ikins	Stratigraphy and paleontology of Walnut and Comanche Peak Fms. in Hays Co. and northward to Hood Co.
1942	A.N. Sayre & R.R. Bennett	Classic description of the reservoir characteristics of Edwards Limestone in south-central Texas
1944	Virgil E. Barnes	Description of Kirschberg evaporite horizon with Edwards Limestone
1952	William O. George	Geology and ground water of Comal Co.

TABLE 1 (cont'd)

YEAR	OBESERVER	DESCRIPTION OF WORK
1955	Roger Rhoades & William Guyton	Ground-water patterns at Canyon reservoir site, Comal Co.
1956	B.M. Petitt Jr. & W.O. George	Ground-water resources of the San Antonio area
1956	Frank E. Lozo & F.L. Stricklin Jr.	Revision of Trinity stratigraphic relationships with emphasis on the division concept
1956	Kenneth J. DeCook	Geology of San Marcos Springs 5' quad, Hays Co.
1957	Terry V. Bills Jr.	Geology and ground-water occurrence in Waco Springs 5' quad, Comal Co. (map overlaps SE part of Sattler 7.5' quad of this report)
1957	A. Peter Noyes Jr.	Geology of a portion of Hays Co.
1957	Victor L. King Jr.	Geology of Mission Valley 5' quad, Comal Co. (map overlaps part of New Braunfels West 7.5' quad in this study)
1959(a)	Keith Young	Faunal relationships within Edwards rudist-banks
(b)		Eight Washita ammonite zones parallel rock unit boundaries, thin toward San Marcos platform and the four lower zones are sequentially overlapped by each overlying zone as Georgetown thins southward onto the Edwards
1961	Kenneth G. Martin	Stratigraphic relationships of Georgetown, Del Rio, and Buda Fms. in south-central Texas
1961	Clyde H. Moore Jr.	Defined members of Walnut Fm. in south-central Texas
1962	Jan A. Winter	Regional study of subsurface Fredericksburg and Washita facies southwest of San Marcos platform and recognition of Stuart City reef trend
1962	Delos R. Tucker	Regional study of subsurface Fredericksburg and Washita facies northeast of San Marcos platform

TABLE 1 (cont'd)

YEAR	OBSERVER	DESCRIPTION OF WORK
1963	Ted Arnow	Geology and ground water of Bexar Co.
1964	Clyde H. Moore Jr.	Walnut-Comanche Peak facies interpreted from measured sections in south-central Texas
1965	U.S. Army Corps Engrs.	Regional Study of Edwards underground reservoir
1966	Patrick L. Abbott	Subdivision of Glen Rose Fm. in Comal Co.
1966	Peter U. Rodda, Wm. L. Fisher, *et al*.	Measured sections and chemical analyses of Lower Cretaceous carbonates of Texas
1966	Keith Young	Ammonite zonation of the Fredericksburg Division
1967	Keith Young	Summary of stratigraphic relationships within the Comanche Series, south-central Texas
1967	William L. Fisher & Peter U. Rodda	Regional stratigraphic relationships within the Edwards Fm. with ideas on occurrence of dolomite and chert
1968	Peter R. Rose	Comprehensive surface and subsurface lithofacies analysis of Edwards Fm. in central Texas
1971	John H. Newcomb	Geology and ground water of 7.5' Bat Cave quad, Comal and Bexar Co.
1971	F.L. Stricklin Jr., C.I. Smith, & F.E. Lozo	Stratigraphy of the Trinity Division, central Texas

Eastern Edwards plateau vegetational province

The uplifted Edwards plateau has been strongly dissected by stream erosion yielding a rugged topography provincially referred to as the "hill country". Its three essential physiographic components are: (1) the gently sloping interstream uplands, (2) the steep slopes of the canyon walls, and (3) the stream courses. The limestone terrane of the Edwards plateau is rife with fissures and springs which keep the streams and their alluvial deposits well supplied with water. Tongues of luxuriant forest growth reminiscent of the moister eastern United States invade an otherwise semi-arid environment. Large trees along the well-watered canyons, but not in the uplands, include the baldcypress (*Taxodium distichum*) and the pecan (*Carya illinoensis*). Also common are the eastern cottonwood (*Populus deltoides*), the American sycamore (*Platanus occidentalis*), the black willow (*Salix nigra*), the American elm (*Ulmus americanus*), and several others.

The divides are dominantly limestone that is carried off in solution by carbon dioxide-charged water. The only particulate matter available to form a soil residuum is the minor percent of clay and sand admixed within the limestone. But the steepness of the slopes allows a rapid runoff that usually erodes the clastic material before a mature soil profile can develop. The area is characterized by thin soils mixed with broken rock slabs that rest on hard limestone. The soils fall into similar series such as Valera, Denton and Brackett (Carter, 1931).

The region annually receives about 32 inches of rain but its distribution in time and space is highly irregular. Several years may receive far less than the mean annual rainfall but then one weeks precipitation may exceed it. The average annual temperature is in the high 60's with winter readings dropping below freezing for short periods and summer values sometimes exceeding 100°. Winds are dominantly from the southeast and evaporation rates are considerably in excess of precipitation.

The eastern Edwards plateau is covered by open grassland, scattered scrub timber, and some timbered country. The timber of the divides is a dry-climate forest picturesquely described by Bray (1904): "The growth is stunted, the wood dense and hard, the branches rigid, the foliage somber, the leaves small and stiff; the climate is written in every feature." The native vegetation is largely short grasses, bunch grasses, abundant junipers, various oaks, mesquite, cacti, and many shrubs. It is predominantly range land and is commonly stocked with combinations of cattle, sheep and goats to make best use of the variety of plants.

The steep limestone slopes and gentler uplands are dominated by a juniper-oak-grass floral association. The most abundant tree is *Juniperus ashei*. This juniper (known as cedar to "hill country" folk) flourishes in the harsh calcareous soils of central Texas and on similar limestone terranes in southern Oklahoma and southeastern Missouri.

Oaks common to the area include *Quercus sinuata* (white or shin oak), *Q. virginiana* (live oak), and *Q. shumardii* (Texas or Spanish oak). Maps of their areal distribution show roughly similar ranges over large parts of the Atlantic and Gulf coastal plains (Fowells, 1965). The westernmost extent of each is separated by a dashed line essentially delimiting the Balcones fault trace. West of this line these oak species have undergone enough ecotypic differentiation while adjusting to the Edwards plateau that they are further recognized by the respective varieties:

breviloba, *fusiformis*, and *texana*. The harsh soils derived from the limestone terrane and the spasmodic rainfall have caused habitat-correlated variation within each species that has created genetically fixed ecotypes. These varieties are also found in southwest Oklahoma and on the east face of the Sierra Madre Oriental.

The most characteristic tree on clay outcrops in the eastern Edwards plateau is the mesquite (*Prosopis glandulosa* var. *glandulosa*) which ranges from Mexico to Oklahoma.

Brief observations on stratigraphic control of larger plants are:

Del Rio	abundant mesquite
Edwards limestone	abundant juniper-oak with increased prickly pear cactus (*Opuntia lindheimeri*)
Edwards terra rosa	numerous mesquite; in southern part of Bulverde quad this habitat increasingly occupied by acacia
Walnut-uppermost 12 to 22 feet of Glen Rose	dense juniper band but with numerous oaks and other more desirable trees giving a distinct light green tonal band
Glen Rose upper dolomite (120 feet thick)	largely barren

REGIONAL GEOLOGIC FRAMEWORK

Structural elements

The Texas craton is a salient of Precambrian basement rocks trending north and west from central Texas that yield radiometric dates hovering about one billion years (Flawn, 1956). The Llano uplift exposes Precambrian granites and metasedimentary rocks of the Texas craton along with arched and faulted Paleozoic rocks. The Llano area yielded terrigenous sediment for Trinity rocks but was progressively buried by Fredericksburg deposition.

The largely concealed Ouachita system is a belt of deformed Paleozoic rocks bordering the southern edge of the cratonic interior of North America analogous to the Appalachian system bordering the eastern edge. The Balcones fault system region of central Texas is underlain primarily by the frontal zone of slightly metamorphosed to unmetamorphosed folded and thrust-faulted rocks reminiscent of the Appalachian Valley and Ridge province. The Ouachita facies are comprised essentially of relatively thin Lower Paleozoic siliceous and dark argillaceous rocks and thick Upper Paleozoic coarse clastic deposits. The bulk of the Ouachita system has been depressed beneath the great sedimentary prisms of the Gulf coastal plain (Flawn, et al., 1961).

Major regional subsidence of the Gulf of Mexico basin occurred during the Late Jurassic and Cretaceous as evidenced by thousands of feet of carbonate rocks in the Yucatan and Florida-Bahama platforms (Murray, 1961). In Texas the basinward tilt of the Gulf's northern flank resulted in a slow transgression of Cretaceous seas which gradually inundated a former low relief land surface (Young, 1962). The sinking of the basin continued through the Tertiary coupled with upwarping of its northwestern margin.

The homoclinally dipping Cretaceous and Tertiary beds along the northern and western flanks of the Gulf are interrupted by synthetic and antithetic systems of <u>en echelon</u> normal faults. The field area of this report lies within the dominantly synthetic Balcones fault system of <u>en echelon</u>, high angle, down-to-the-coast normal faults (figure 2). This system forms a convex-to-the-coast arc averaging 10 to 12 miles in width and paralleling the trend of the subjacent Ouachita system as it bends around the Texas craton. The stratigraphic displacement across Comal County totals about 1400 feet. Coastward from and parallel to the Balcones system is the primarily antithetic Luling system of up-to-the-coast normal faults whose aggregate displacement is about 450 feet. The synthetic Balcones system and the antithetic Luling system create an intervening graben.

The classic explanation of Balcones faulting utilizes the crustal extension caused by subsidence of the Gulf of Mexico geosyncline and the accompanying uplift of the Edwards plateau (Foley, 1926). The Cretaceous rocks lying on the supporting Llano positive element were subjected to maximum stretching across its stable margin. Release of these tensional stresses created a down-to-the-coast fault system whose trend paralleled the hinge line created by the boundary of the Texas craton.

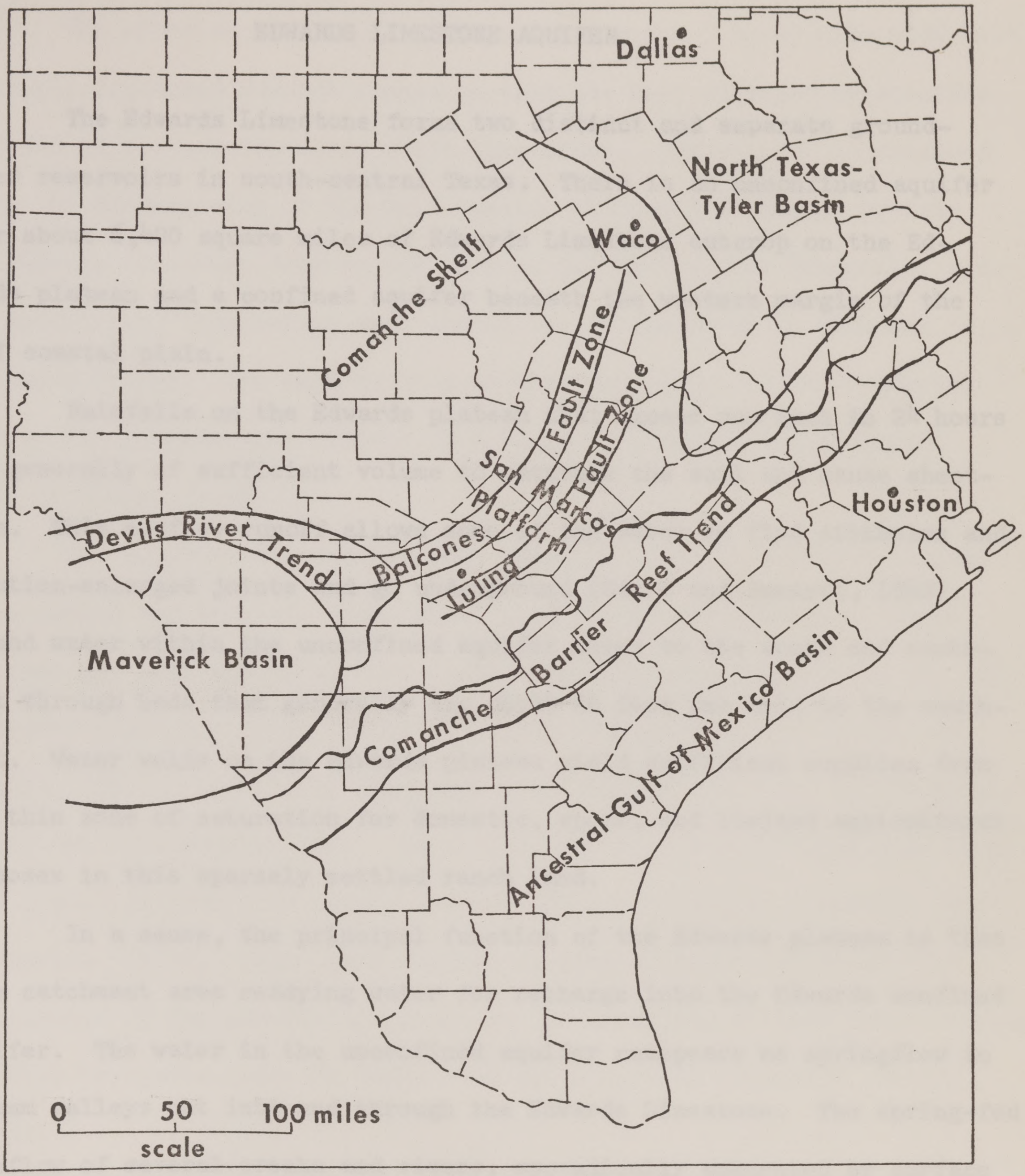
Facies patterns within Comanchean rocks show no effects of Balcones fault movement during their deposition. Thin beds within the Austin

Division and a Baculites zone in the Pecan Gap chalk of the Taylor Division carry across the fault line indicating no displacement up to that time (Keith Young, oral communication, 1971). The first positive evidence of movement on the Balcones fault system is shown by the abundant reworked Upper Cretaceous fossils and limestone fragments in the Early Miocene Oakville Formation (Weeks, 1945). It seems that most Balcones faulting was restricted to the Miocene (Young, 1962).

Depositional elements

During most of the Early Cretaceous a great barrier reef existed on the shelf edge that separated the shallow interior of Texas from the deeper ancestral Gulf of Mexico basin. These linear bioclastic ridges were named the Comanche barrier reefs by Hendricks and Wilson (1967).

Deposition of Lower Cretaceous rocks in central Texas occurred on a broad, essentially flat, usually submerged, back-reef surface designated the Comanche shelf by Rose (1968). The shallow water Comanche shelf was partially bordered by depressions and rises that affected the depositional fabric. The most significant depressions were the North Texas-Tyler basin (Fisher and Rodda, 1967) to the northeast and the Maverick basin (Winter, 1962) to the southwest. The northern rim of the Maverick basin had a shallow-water belt of bioclastic debris known as the Devils River trend. The field area of this report was on the intervening arch known as the San Marcos platform. The position of this area of lesser subsidence than the basins to the northeast and the southwest was probably largely controlled by the subjacent Texas craton. The location of the crest of the San Marcos platform is inferred from the erosion of the upper Person and the thinning of the Georgetown, Del Rio, Eagle Ford, and Austin Formations.



REGIONAL GEOLOGIC FRAMEWORK

Figure 2

EDWARDS LIMESTONE AQUIFER

The Edwards Limestone forms two distinct and separate ground-water reservoirs in south-central Texas. There is an unconfined aquifer over about 6,400 square miles of Edwards Limestone outcrop on the Edwards plateau and a confined aquifer beneath the western margin of the Gulf coastal plain.

Rainfalls on the Edwards plateau that exceed one inch in 24 hours are generally of sufficient volume to saturate the soil and cause sheet-wash. This surface runoff allows some of the water to find sinkholes and solution-enlarged joints and go underground (Sayre and Bennett, 1942). Ground water within the unconfined aquifer moves to the south and southeast through beds that generally dip about 20 feet per mile to the southeast. Water wells on the Edwards plateau yield sufficient supplies from the thin zone of saturation for domestic, stock, and limited agricultural purposes in this sparsely settled ranch land.

In a sense, the principal function of the Edwards plateau is that of a catchment area readying water for recharge into the Edwards confined aquifer. The water in the unconfined aquifer reappears as springflow in stream valleys cut into and through the Edwards Limestone. The spring-fed baseflow of several creeks and rivers, sporadically augmented by surface runoff, moves across the Glen Rose outcrop for some distance and then largely goes underground where it crosses the fractured and cavernous limestones in the Balcones fault zone, especially in Uvalde and Medina Counties.

The artesian aquifer is a 250 mile long and 5 to 40 mile wide belt of highly fractured Edwards Limestone that has been enlarged by solution gulfward of the main Balcones fault-line scarp. The aquifer is confined below the western edge of the Gulf coastal plain and Blackland prairie and extends southwest from Austin through San Marcos, New Braunfels, and San Antonio and then swings west across the Devils River to Comstock in Val Verde County. The segment of most interest is the 175 mile stretch between the ground-water divides at Kyle in Hays County and Brackettville in Kinney County.

The southern and southeastern boundaries of the artesian aquifer are a marked and mappable "bad water" line where dips steepen to about 100 feet per mile and total dissolved solids increase from 250 to 450 mg/l to around 1,000 mg/l; the latter including hydrogen sulfide (Sayre and Bennett, 1942). No springs discharge south and east of this line and well yields are considerably less. Apparently the only natural discharge from this region is from slow upward leakage (Robert W. Maclay, personal communication, 1973). These data suggest an area of lesser permeability development in the Edwards Limestone due to bypassing of most water through the more permeable Balcones fault zone which acts as a regional master conduit.

A deviation from classical ground-water movement theory was noted in this region by Sayre and Bennett in 1942. The generalized contours on the potentiometric surface of the Edwards Limestone artesian reservoir in Kinney, Uvalde, Medina, Bexar, and part of Comal Counties are generally parallel to the strike of the beds, i.e. east and northeast. Thus, ground water would be expected to move south and southeast across the "bad water" line but it obviously does not. Measurements of recharge and discharge show excessive recharge in Uvalde and Medina Counties coupled with excessive discharge in Comal County. Hence, large quantities of water apparently move through pipes created by dissolution of carbonate rock subparallel to the northeast-trending faults and at an acute angle to regional potentiometric surface contours. However there is no doubt that if sufficient water level data were available to map the potentiometric surface, the flow lines would trend northeastward and would be at right angles to the potentiometric contours.

after Sayre and Bennett (1942)

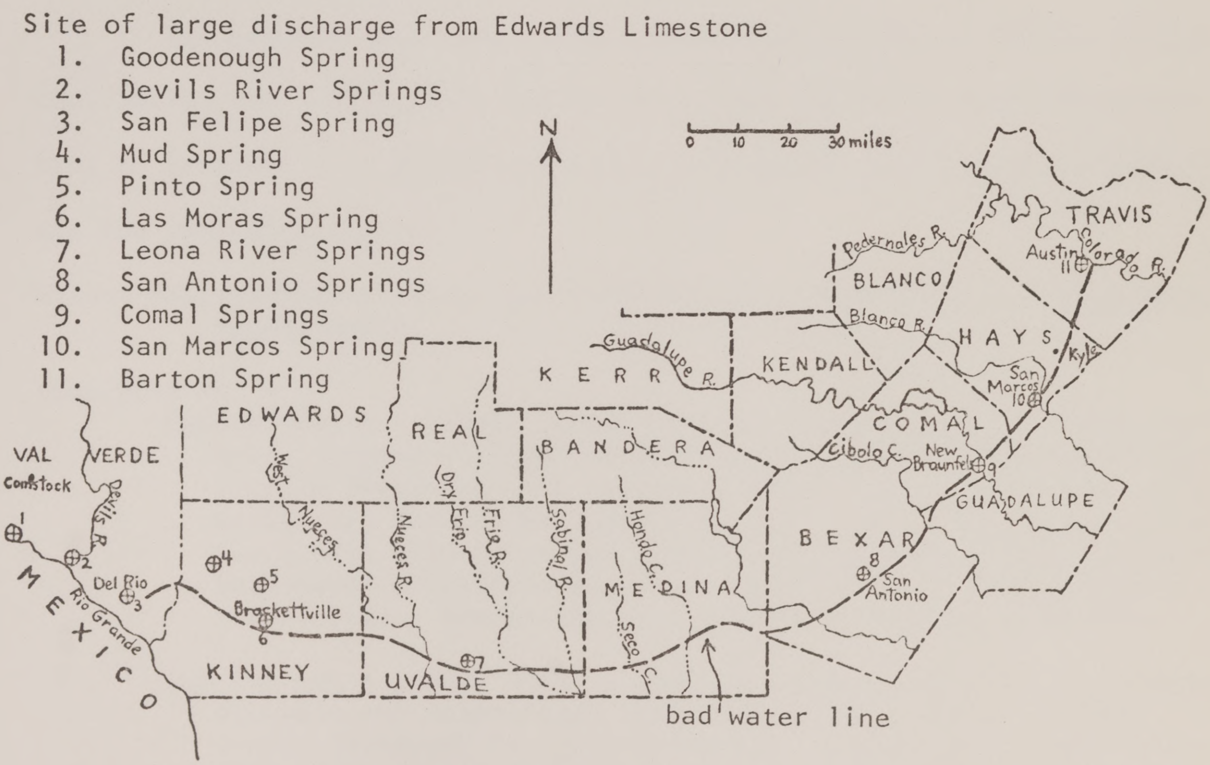


Figure 3 LARGE SPRINGS AND BAD WATER LINE IN EDWARDS LIMESTONE

The 175 mile long segment of the Edwards underground reservoir supplies the water for more than 900,000 people. This includes the domestic and industrial needs of the city of San Antonio, other towns, agricultural irrigation, four U. S. Air Force bases, and the U. S. Army's Fort Sam Houston. Water discharges from thousands of wells and numerous springs including several of the largest in the United States.

Ironically, though urbanization, industrialization, and agricultural irrigation grow rapidly and without limits, the total storage capacity of the artesian resevoir they all depend upon is unknown.

STRATIGRAPHY

The stratigraphy of central Texas has been studied since the days of Römer (1846) and Shumard (1860). The history of the stratigraphic nomenclature is given in Table 2.

Glen Rose Formation

Lithology. The Glen Rose Formation in this report area is comprised of roughly 700 feet of alternating marls, fossiliferous limestones, and dolomites with some coral or rudist reefs and evaporite horizons. The Glen Rose has long been separated into upper and lower members by the "*Corbula* bed", an intraclastic biosparite with profuse *Corbulae herveyi* Hill. The bed is 1-2 feet thick and covers several thousand square miles.

The sequence has been further subdivided by Abbott (1966), Stricklin, Smith, and Lozo (1971), and by Lyman Dawe (U. Texas Ph.D. dissertation in progress). A generalized section compiled from the above workers and the present study is:

Walnut Fm. - Pseudosparites, sandy intraclastic biosparites, and *Exogyra texana* marls.

Glen Rose Fm. -

Subdivision L - (12-22 feet) - Grunge zone. Usually a steep, covered, recessive slope beneath resistant Walnut pseudosparites. Densely populated with junipers, scrub live oak, Spanish oak, hackberry, Mexican persimmon, *et al*. Rare exposures show plastic clays, boxworks after evaporites, calcite crystal geodes, carbonate concretionary bodies, punky dolomite, and honeycombed beds. Presumably an evaporite-condensation horizon.

Subdivision K - (120 feet) - Upper dolomite. Abundant replacement dolomite and dolomitized intraclastic miliolid biomicrite. Common lithology is leached-looking dolomite with moldic porosity after fossil fragments and miliolids. Distinctive outcrop-- whitish slope barren of vegetation with some resistant dolomite ledges sticking out.

Subdivision J - (90 feet) - Steinkern marls. Whole mollusc-echinoid marls with miliolid biomicrites and dolomites. Numerous beds contain rudaceous snails, clams and sea urchins along with oysters and miliolids. Few small *Monopleura* patch reefs. Several layers are dolomitized.

Subdivision I - (30 feet) - Clayey dolomite with dolomitized biomicrite and marl. A couple of intraclastic biosparites.

Subdivision H - (45 feet) - Intraclastic miliolid biomicrite and poorly washed biosparites with interbedded marls and superficial oosparites.

Subdivision G - (85 feet) - *Orbitolina texana* biomicrite and marl with a several feet thick, resistant caprinid biolithite ledge about 1/3 of the way up into the subdivision. The biolithite is apparently an aquifer in some places.

Subdivision F - (50 feet) - Dolomites, dolomitized biomicrites and marls. Upper part is clayey flagstone.

Subdivision E - (55 feet) - Lower part is flaggy beds of clayey-sandy micrite, dolomite, and boxworks after evaporite beds. In upper part conditions were more normal marine as shown by small *Monopleura* patch reefs, an oyster bank, *Orbitolina texana* marl, and other marls. Uppermost unit is the richly fossiliferous *Salenia texana* marl which is capped by the "*Corbula* bed". The profusion of "*Corbula*" steinkerns indicates a return toward hypersalinity that is reflected in the superjacent subdivision.

Subdivision D - (20 feet) - Caprinid biolithite with associated talus. *Toucasia* and *Monopleura* become common near the top. This unit apparently is an aquifer in some areas.

Subdivision C - (25-50 feet) - *Orbitolina texana* marl with lignitic plant fragments.

Subdivision B - (60 feet) - Sparse biomicrite with subdued alternating bed topography. Fauna is diverse but sparse and largely fragmented. Some beds are intraclastic. Upper 15-30 feet sometimes has distinctive white chalky appearance.

Subdivision A - (100 feet) - Oolitic intraclastic biopelsparite--largely made up of shell banks with pellets and intraclasts; also rudist and coral biostromes and dunes of superficial oolites. Diverse fauna of clams, snails, rudists, oysters, echinoids, *Orbitolina*, coral, serpulids, bryozoa, ostracods, *et al.* Differential solution of various allochems typically produces a honeycomb porosity system. Springs issue from throughout this subdivision and commonly along the solution-enlarged bedding contact with the lesser permeable, subjacent Hensel Formation.

Hensel Fm. - Sandy dolomites above glauconitic, sandy recrystallization limestone.

Aquifer characteristics. The Glen Rose Formation generally exhibits low permeability and its relatively small amount of confined ground water is available to wells from distinct lateral zones; vertical movement is slight (Rhoades and Guyton, 1955). Unlike the essentially pure carbonate rocks of the Edwards, most of the Glen Rose is characterized by a number of intercalated marls (alternating beds). These ubiquitous aquitards have been inimical to overall aquifer development.

The Glen Rose horizons that commonly yield water are the honeycombed shellbank in the lower half of subdivision A, the caprinid biolithites making up subdivision D and a small part of G, and the upper dolomite (subdivision K) near the eastern edge of the Edwards plateau. It is frequently necessary for well bores to penetrate through the upper Glen Rose and into the lower beds in order to secure a total yield of several gallons per minute. Commonly, wells drilled through such a section have yields insufficient even for household and livestock watering purposes. Numerous wells produce low quality water high in total dissolved solids. This indicates sluggish water movement through low permeability rocks.

The best aquifer in the Glen Rose is the massive, basal honeycombed shell mounds, from which emerge some of the larger springs in Comal County (e.g. Spring Branch, Honey Creek, Cranes Mill, and Devils Hollow). Century and Cascade Caverns in Kendall County are developed in this interval.

The base of Canyon dam sits on the lower Glen Rose (subdivision E) and it apparently has been sealed almost tight by grouting. The Estrellita ranch (first spread completely east of the Guadalupe river on FM 306, Sattler quadrangle) reports that five of their six wells went completely dry in 1966, two years after completion of the dam. Only a well yielding water high in sulfates continues to produce at all. Grouting effective enough to seal off all recharge from wells placed through the river floodplain just 2.5 miles downstream from a major reservoir could only take place in rocks of very slight permeability.

Many small springs, essentially seep springs, issue from the upper Glen Rose even during dry periods. However these largely reflect local perched water bodies in rocks of low permeability. The maximum yield for most water wells in the upper Glen Rose is probably less than three gallons per minute (George, 1952).

In total, the Glen Rose Formation above its basal 50 feet is best described as a low permeability rock body with a few low productivity aquifers that are poorly connected vertically. However there are some notable exceptions to this generalization near the eastern edge of the Edwards plateau. Both Natural Bridge Caverns and Bracken Bat Cave are developed largely within the upper dolomite (subdivision K) of the Glen Rose (figures 7 and 8) in direct association with the Bat Cave fault. Typical yields from the upper dolomite in this area are commonly 20 to 30 gpm versus the ordinary 0 to 3 gpm (Newcomb, 1971).

Although the Glen Rose Formation ordinarily makes a tight bed for streams to flow across a significant cavern system has developed beneath Cibolo Creek.

TABLE 2. ORIGIN OF STRATIGRAPHIC NOMENCLATURE

COMANCHE SERIES: Used as a provincial time-rock term for the Lower Cretaceous by Hill (1887a) who first studied the interval around the town of Comanche, Texas, in a region formerly inhabited by the Comanche Indians. Hill (1887, 1889) thought the Series represented essentially unbroken sedimentation in three lithologically and paleontologically distinct Divisions.

WASHITA DIVISION: Name first applied by Shumard (1860) to beds underlying the "*Exogyra arietina*" marl (i.e. Georgetown Fm.) near old Fort Washita, Oklahoma. Hill (1887a) borrowed the term for the upper Division of his Comanche Series.

Del Rio Clay: Appellation derived by Hill & Vaughan (1898) from town of Del Rio in Val Verde Co., Texas, for the southern extension of the Grayson Marl of North Texas.

Georgetown Limestone: Initial label by Vaughan (1900) at Hill's suggestion. Hill (1901) used the name for the limestone-marl sequence between the Edwards and Del Rio exposed along the San Gabriel River near Georgetown in Williamson Co., Texas.

Kiamichi Fm.: Originally called Kiamitia clays by Hill (1891) for outcrops in the Kiamichi River plain near Fort Towson, Choctaw Co., Oklahoma.

FREDERICKSBURG DIVISION: Hill (1887a) correlated rocks in the Fort Worth area with Roemer's Fredericksburg sections then drew his name from the Gillespie Co. city. Hill's definition of this Division changed repeatedly but stabilized in its present form in a 1937 paper.

Edwards Fm.: Originally called *Caprina* limestone by Shumard (1860), then Barton Creek limestone by Hill (1889), and finally acquired its present name from the Edwards plateau (Hill & Vaughan, 1898). Adkins (1933) placed the type section on Barton Creek in Austin, Texas. Rose (1968, 1972) has elevated the interval to Edwards Group with Kainer (lower) and Person Fms. including several members. Of particular use is the Regional Dense Mbr. (lowermost) of the Person Fm.

Comanche Peak Fm.: Shumard (1860) derived the name from an Indian Landmark in Hood Co., Texas.

Walnut Fm.: Hill (1891) applied this label to occurrences around Walnut Springs in Bosque Co., Texas. The lower limestone and lower marl units were respectively designated the Bull Creek and Bee Cave Members by Moore (1961).

TRINITY DIVISION: Appellation taken from the Trinity River valley in north-central Texas by Hill (1889) to describe the lowest subcycle of the Comanche Series.

Glen Rose Fm.: Sequence entitled *Caprotina* limestone by Shumard (1860), called "alternating beds" by Hill (1889), and designated Glen Rose Fm. by Hill (1891) after the town along the Paluxy River in Somervell Co., Texas.

Upper contact. The top of the Glen Rose is placed above a 12 to 22 feet thick, steep and recessive covered slope beneath the stripped surface on the resistant pseudosparites of the basal Walnut. Infrequent exposures of this interval show plastic clays, boxworks after evaporites, void fillings of secondary calcite, and punky dolomites that suggest an evaporite interval representing the terminal hypersaline event of the thick upper dolomite subdivision of the Glen Rose. These evaporitic deposits have been leached and now appear as a condensed residue of the above (plate 6A), hereafter referred to as the grunge zone.

The uppermost unit is readily recognized by its steep slope, its place beneath the shallow slope of the Walnut, its position above the unvegetated upper dolomite of the Glen Rose, and its dense juniper growth.

Walnut Formation

Lithology. At least in the counties of Comal, Bexar, and Blanco the Walnut Formation exists as a mappable, 30 to 50 feet thick rock body of distinctive lithologies, weathering profile, and diagnostic pristine vegetation. These beds are immediately above the thick upper dolomite and grunge zone of the Glen Rose and are below the typical burrow-mottled, dolomitized miliolid-rudist grainstones and wackestones of the lowermost Edwards.

The lower lithologies are mostly pseudosparites and sandy intraclastic biosparites like the Bull Creek Member of the Walnut Formation in Travis County. The upper beds are mostly sparse *Exogyra texana* marls with intervening clayey biomicrites strongly reminiscent of the Bee Cave Member of the Walnut Formation (plate 6B). The basal Bull Creek-like lithologies are customarily stripped to form a shallow sloping surface. The average slope angle increases upwards and is punctuated by even steeper recessive slopes on the marl beds.

The trees growing on the Walnut Formation are more varied than the typical drab green juniper-scrub live oak association ordinarily found on the Glen Rose and Edwards. Numerous Texas oaks, along with the hackberry and other trees, give a distinct light green tonal band to the Walnut outcrop (plate 6C).

The Walnut Formation is usually not used in this area, or else it is treated as an unmappably thin or barely mappable Exogyra texana marl (e.g. George, 1952; Bills, 1957; U. S. Army Corps of Engineers, 1965; Rose, 1968). In lieu of recognizing the Walnut, The U. S. Army Corps of Engineers and some U. S. Geological Survey geologists raise stratigraphically the Glen Rose-Comanche Peak* or Glen Rose-Edwards contact. This places numerous normal marine, or even brackish water, Exogyra texana marls and sandy intraclastic biosparites in with the hypersaline deposits of the upper Glen Rose. This seems unsatisfactory because historically these units have been classified on genetic sedimentary cycles, and the boundary is between hypersaline and brackish with this cycle. The Glen Rose Formation should terminate at the top of the upper dolomite in the subsurface or above the upper dolomite and evaporitic grunge interval in

*Although the term Comanche Peak Formation has not been used in this work there exists a distinctive lithology that differs from typical Comanche Peak but occupies its geometric position between the Walnut and Edwards. It is a dolomitized rudist biolithite and biomicrite with large burrow mottles. Although it can be recognized as a rather distinctive lithology in outcrop and cores it has a gradational upper boundary, nondescript weathering profile, and ordinary juniper-scrub live oak flora that make it unuseful for mapping.

the Balcones fault zone.

Instead of utilizing a Walnut unit, Rose (1968) lowers the Edwards-Glen Rose contact to include all but the lowest E. texana marl into the Edwards. Beds of Walnut Formation lithology lose their identity in the 260 feet thick Dolomitic Member of the Kainer Formation of the subsurface or are almost identified as the 50 feet thick Basal Nodular Member of the Fort Terrett Formation of the Edwards plateau.

On the Edwards plateau the interval between the Glen Rose upper dolomite and Edwards rudist biolithite and biomicrite is occupied by E. texana marl, silty marl, and calcareous claystone. The Walnut Formation has customarily included much terrigenous detritus which decreases to minor percentages in the Balcones fault zone. However, Rose (1968) places the lower barren marl and claystone of this interval into the Glen Rose and the upper fossiliferous marl into his Basal Nodular Member.

In cores taken from beneath the Gulf coastal plain the Walnut contains easily recognized, diagnostic fossil fragments stained by disseminated, reduced iron (black rotund bodies or BRB's) along with abundant Exogyra texana biomicrite and marl. In fresh cores the upper contact appears gradational. The lower part of the Walnut has a couple of intercalated dolomites but the contact of the lowermost E. texana marl and the thick upper dolomite of the Glen Rose is sharp and distinct.

The roughly 22 feet thick Regional Dense Member makes a valuable map unit that divides the Edwards. Likewise the Walnut Formation is another distinctive marker horizon and map unit throughout the Balcones fault zone region of south-central Texas.

PLATE 6

A. Finely crystalline, porous (intercrystalline and moldic after fossils), replacement dolomite beds of the Glen Rose Fm. 'upper dolomite' (subdivision K) overlain by the honeycombed, evaporite-condensation, 'grunge zone' (subdivision L). Photographed at the David A. E. Ackermann Ranch along Mud Creek in west-central Bulverde quadrangle.

B. Stream bed cut through corrosion surface on 'Bull Creek'-like intraclastic biosparite. Pronounced recessive interval is developed on a 'Bee Cave'-like Exogyra texana marl. Main cliff-forming beds are dolomitized caprinid banks and biomicrites of lowermost Edwards Group. Photo taken at mouth of Isaac Creek at 1st crossing of Guadalupe River.

C. Guadalupe River cutbank exposure of the Glen Rose, Walnut, and Kainer Formations. Photo taken just northeast of center in Sattler quadrangle.

D. Rudist banks and intraclastic, skeletal debris grainstones of the uppermost Person Fm. blanketed by clayey, sparse biomicrite of the Georgetown Fm. Topographically highest roadcut on Loop 337 South in the New Braunfels West quadrangle.


grunge
upper dolomite
A


Edwards
'Bull Creek'
B


Kainer
Walnut
Glen Rose
C


Georgetown
Person
D

Porosity characteristics. Void space development in the Walnut Formation is negligible and by and large the unit can be viewed as an aquitard. This is in spite of the occurrence of random large megapore vugs and occasional caverns (e.g. Natural Bridge Caverns and Bat Cave) which pass through it.

The Walnut and Comanche Peak Formations below the Edwards Group and the Georgetown Formation above have been described as the Edwards and associated limestones for hydrologic purposes. This seems rather unnecessary as almost all the significant porosity and permeability is in the Edwards Group proper.

Edwards Group

Lithology. A composite section of the Edwards Limestone on the San Marcos platform is about 400 feet thick. Lithologies are dominantly sparse miliolid-fossil fragment biomicrite and oyster-rudist biolithite with reworked skeletal debris. The beds of Edwards Limestone are relatively pure (i.e. free from terrigenous sediment) calcarenites and calcilutites that have undergone extensive dolomitization, chertification, and recrystallization throughout the section. Original lithologic attributes suggest the dominant depositional environments were supratidal and intertidal flats with subtidal or mini-lagoonal lows around oyster-rudist banks and skeletal grain barriers.

The subsurface Edwards Formation has long been split into Edwards 'A' and 'B' units at a 'kick' in electric log profiles caused by a dense marker bed. This Regional Dense Marker is a clayey biomicrite approximately equivalent to the Kiamichi Formation of North Texas and the Doctor Burt ammonite beds of the Edwards plateau. Rose (1968, 1972) created regional nomenclatural stratigraphic frameworks within the Edwards Limestone on both sides of the Balcones fault zone. Rose (1972) formalized the traditional subsurface Edwards by raising the interval to an Edwards Group with Kainer (lower) and Person Formations separated at the base of the Regional Dense Member which is the basal unit of the Person Formation (figure 4). This terminology was also suggested for the Edwards Limestone in the Balcones fault zone.

On the Edwards plateau the readily identifiable Doctor Burt ammonite beds were used to split the Edwards Group into Fort Terrett (lower) and Segovia Formations (Rose, 1972). The Fort Terrett was partitioned into members and the Segovia section red-flagged with key beds (figure 4). This terminology was suggested for the Edwards plateau to the west of the Balcones fault zone only. However, the Kirschberg Evaporite Member of the Fort Terrett is recognizable in some measured sections in the Balcones fault zone (e.g. Colorado River bluff and U. S. Gypsum quarry sections in appendix).

Usefulness of Members of Kainer and Person Formations in Balcones fault zone. Recognition on the outcrop of stratigraphic position within the Edwards Limestone is complicated by faulting. In addition, the exposed rocks commonly have been dolomitized, chertified, recrystallized, and dedolomitized with a resultant loss of uniqueness that tends to homogenize the different depositional facies. In the field the Dolomitic Member and lower part of the Grainstone Member of the Kainer Formation plus the Leached, Marine, and Cyclic Members of the Person Formation are unrecognizable by themselves.

The Regional Dense Member separating Kainer from Person

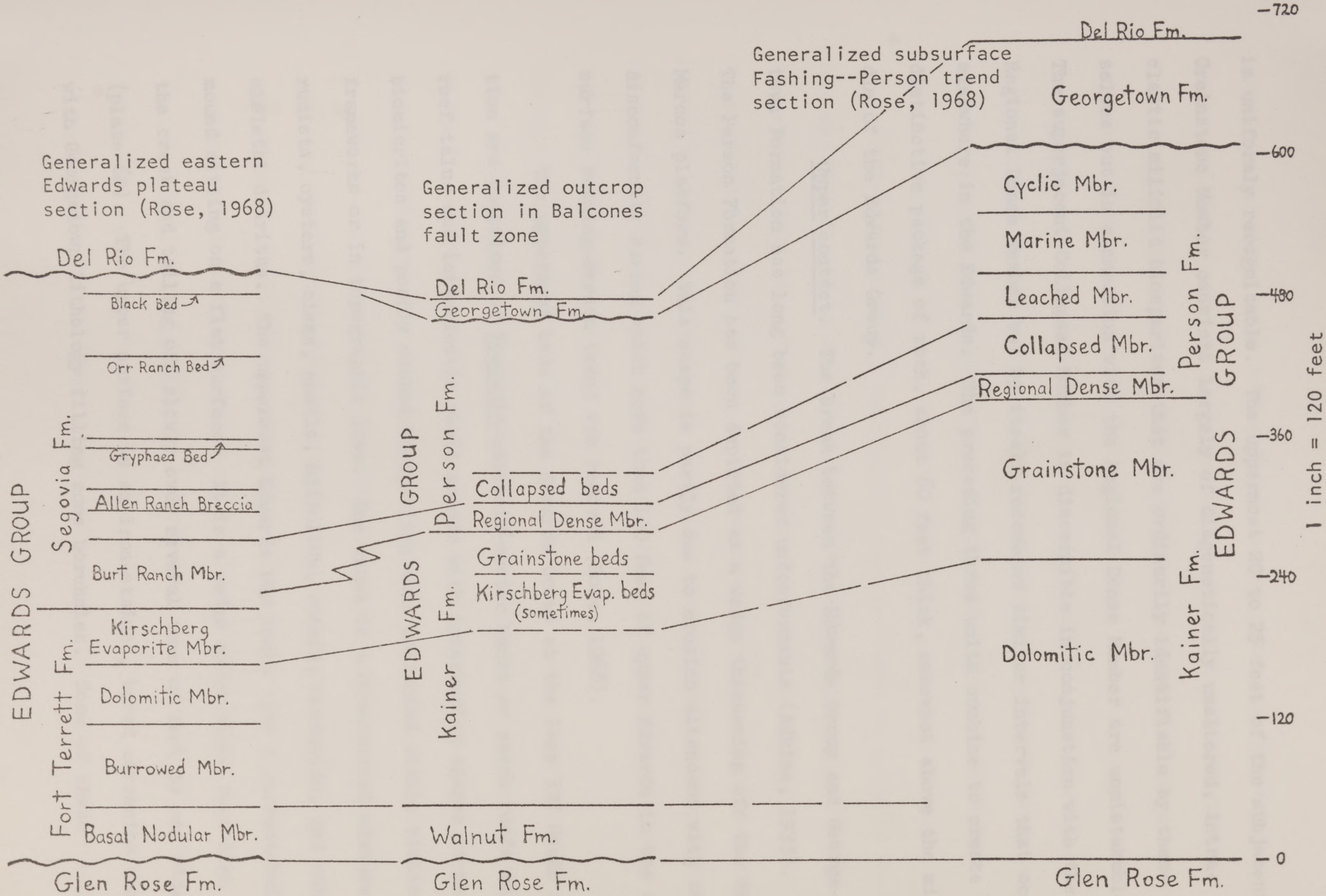


Figure 4 GENERALIZED SECTIONS OF EDWARDS GROUP

is uniformly recognizable. The uppermost 20 to 25 feet of the subjacent Grainstone Member consists largely of diagenetically unaltered, intraclastic miliolid biosparites that are ordinarily identifiable by themselves but in connection with the Regional Dense Member are unmistakable. The superjacent Collapsed Member is discernible in conjunction with the Regional Dense Member but by itself resembles similar intervals that occur elsewhere in the Edwards. The preceding three units combine to create a distinctive package of rock, about 60 feet thick, somewhat above the middle of the Edwards Group.

Upper contact. The break between the Edwards Group and Georgetown Formation has long been considered unconformable (Adkins, 1933). The Person Formation has been depicted as a wedge thickening off the San Marcos platform. This shape is partly due to erosion attendant with the disconformity during which more than 100 feet of upper Edwards in the subsurface Fashing-Person trend was removed (Rose, 1968).

The uppermost beds of the Edwards Group at the Loop 337 South section are comprised of *Toucasia*-caprinid-oyster banks or patch reefs amid reef talus and intraclastic shell mounds with intervening sparse to packed biomicrites and poorly washed biosparites that collected within biolithite frameworks or in topographic lows. The fauna is a diversified mixture of rudists, oysters, clams, snails, miliolids, corals, echinoids, and other skeletal detritus. The uppermost Edwards bed looks like a current-built mound sitting on a flat surface. It is a wedge about three feet high at the crest and tailing off slowly over several tens of feet to one side (plate 6D). The upper surface is an iron-stained, bored corrosion surface with Georgetown lithology filling some boreholes. Some of these ichnofossils appear to be soft sediment burrows that are filled with Georgetown biomicrite. Blanketing this topography on the Edwards is a nodular, argillaceous, sparse fossil fragment biomicrite of the Georgetown Formation.

The upper 20 feet of Edwards at the Loop 337 South section contains orangish-beige oyster biomicrudites and has a marked decrease in porosity suggesting a gradational change toward deposition of Georgetown lithologies.

The Edwards in the Randolph AFB core is capped by a highly angular and etched surface on a partially recrystallized Toucasia-miliolid limestone. This irregular relief surface is filled by pyritic Georgetown biomicrite. The Edwards is recrystallized and has solution-enlarged porosity whereas the Georgetown is clayey, unrecrystallized, has a diverse and different fauna, and is nonporous. This supports the interpretation of an unconformity.

Georgetown Formation

Lithology. The argillaceous sparse biomicrites of the Georgetown Formation are about 17 feet thick. Lithologies vary from unburrowed, clay-seamed wackestone with diverse and numerous whole molluscs and brachiopods to extensively burrowed oyster-fossil fragment biomicrite. The Georgetown beds are distinctive because of their nodular to marly weathering, pervasive limonite stain, fauna, terrigenous clay content, lack of recrystallization or chertification, and absence of solution-enlarged porosity.

Porosity characteristics. Cores (see appendix) reveal a few scattered vugs but permeability is lacking. The Georgetown can be considered along with the Del Rio Clay as part of the superjacent aquitard sealing off the Edwards.

Del Rio Formation

Lithology. The only Del Rio Clay in the map area is found within collapse sinkholes. The exposed lithology is a grayish-orange, calcareous claystone or marl with Exogyra arietina shell placers about one foot thick. The Del Rio is recognized by its lithology, color, fossils, mesquite cover, and steep recessive weathering profile.

DEDOLOMITIZATION

Dedolomitization is a process wherein magnesium ions added to aragonite and/or calcite to form dolomite are themselves purged by a later influx of calcium ions. The process is thought to follow the equation originally formulated by von Morlot in 1848 (Evamy, 1967):

$$CaCO_3 \cdot MgCO_3 + Ca^{++} \longrightarrow 2CaCO_3 + Mg^{++}.$$

The idealized conditions for creation of dedolomite exist where permeable dolomite beds are subjected to continuously circulating, near surface, calcium sulfate-saturated (high Ca/Mg ratio) ground water whose temperature is less than 50° C. and carbon dioxide partial pressure is much less than 0.5 atmosphere (Evamy, 1967; de Groot, 1967).

Dedolomite occurs in carbonate rocks beneath and within collapse breccias that have resulted from solution of underlying evaporite beds. Here, ground water enriched in calcium (i.e. high Ca/Mg ratio) from dissolution of gypsum and/or anhydrite has passed through dolomite and dolomitized limestone beds with a resultant exchange of calcium for magnesium that has converted the dolomite back to calcite.

Dedolomite is a common, though not volumetrically significant, product of surface weathering. Its presence has been suggested as a means of recognizing unconformities in carbonate rock sequences (Chafetz, 1972).

In a study of the Edwards Limestone near Waco, Nelson (1959) recognized "post-lithification calcitic dolomite" or dolomite cemented by secondary calcite. From x-ray diffraction analyses Nelson (1959) concluded that not much dolomite was lost during cementation. However his report of corroded dolomite crystals and poikilotopic calcite cement in optical continuity with dolomite crystals suggests that limited dedolomitization may have occurred.

Dedolomite may be significantly more common than is generally assumed. For instance, the West Sister Creek section, to the west of the main ground-water aquifer in the Balcones fault zone, and the Randolph AFB core, to the east of the main aquifer across the bad-water line, seem to have significantly more dolomite than the stratigraphically equivalent rocks within the Balcones fault zone. All these rocks formed in similar depositional environments but apparently have varying amounts of dolomite. The significant difference appears to be whether or not they were subjected to large quantities of meteoric ground water. These observations have largely been made with a hand lens and are just speculations. Nevertheless it appears that significant amounts of dedolomite have been formed by the ground water which has moved through the Edwards Group.

CHERT

Occurrence

Chert occurs primarily as granule- to boulder-sized nodules elongate parallel to bedding (plate 7C) but is also present as irregularly shaped nodules, as casts after fossils, and in dense, pervasive fronts. Relict textures commonly display fossils and dolomite rhomb outlines although many chert nodule interiors are relatively featureless.

Outcrop observations indicate an apparent association of chert with the more porous and permeable carbonate beds. Chert nodules are commonly found in grainstones with high energy sedimentary structures and seem much rarer in less permeable biomicrites. Where chert occurs in biomicrites it occasionally appears shaped as if it filled the more permeable burrows (plate 7D).

Dolomites, with their intercrystalline porosity, are common hosts for chert nodule nucleation. The outer perimeter of unweathered chert in dolomite taken from cores is occasionally markedly jagged and irregular.

Chert within the Edwards Group is of secondary origin, is associated with high permeability grainstones, is regionally co-extensive with dolomite formed at lagoon margins, and is absent in reef-core and reef-flank facies (Fisher and Rodda, 1969).

Origin

The origin of chert has not been successfully explained by inorganic solution chemistry although many descriptive data exist. The equilibrium solubility of silica is essentially the same in fresh or sea water and ranges from about 7 to 14 mg/l for quartz up to 100 to 140 mg/l for amorphous silica. Silica goes into true solution, mostly as silicic acid (H_4SiO_4; $K_1 = 10^{-9.9}$), a tetrahedrally coordinated monomer with the ability to polymerize. Solubility increases as temperature rises but is unaffected by pH until it surpasses 9. In the lab, supersaturated H_4SiO_4 solutions do not crystallize but form colloidal particles. Concentrations up to several hundred mg/l silica exist as a stable sol and even higher concentrations are necessary to form gels (Krauskopf, 1956).

Silica concentrations cluster around 1 to 6 mg/l in oceans, 13 to 14 mg/l in streams, and 15 to 60 mg/l in deep formation waters (Livingstone, 1963; Davis, 1964). A solution must be supersaturated with respect to amorphous silica before inorganic precipitation can occur but the only supersaturated natural waters are some thermal springs and soda lakes.

Most discussions on the origin of chert pinpoint the silica source as being either from volcanic or biogenic materials. Because the silica concentration in sea water is so low many authors believe that a volcanic source is requisite to create chert. However, in the Gulf of California, despite low absolute silica concentrations, upwelling continuously supplies enough silica so that diatom tests are the dominant sediment in some basins (Calvert, 1966). Of course, in a volcanically active region there clearly exists a ready source of amorphous silica that could be transformed into chert during diagenesis. However it is doubtful that the sea water itself becomes so supersaturated that it precipitates silica directly. This is because of the slow reaction rates of silica compared to relatively rapid water mixing, the established observation that diatoms bloom when excess silica is available, the clay buffer system, and zeolite formation (e.g. phillipsite).

There is no evidence of volcanic detritus in the Edwards Group so the silica source for its chert must be reconstituted biogenic material; most likely, siliceous sponge spicules.

About 90 percent of the excess silica delivered by rivers to the oceans is apparently involved in a reverse weathering process (MacKenzie and Garrels, 1966):

$$\text{x-ray amorphous-Al-silicate} + HCO_3^- + SiO_2 + \text{cations} \rightleftharpoons \text{cation-Al-silicate} + CO_2 + H_2O$$

The remaining 10 percent of excess silica is utilized by organisms (diatoms, radiolarians, siliceous sponges, silicoflagellates) that have an ability to extract silica even in very dilute solutions. In life the opaline tissue is protected from dissolution by films of organic matter and adsorbed inorganic cations like Al^{+++}. After death the protective cover of these organisms disappears and silica dissolves. This partly explains why the interstitial water of sea floor sediments has a higher silica concentration than the overlying water body.

From this point on the work of geochemists and petrographers merges into ill-defined statements about the partial dissolution and redeposition of silica along pH differentials over a small range within microenvironments. For example, during diagenesis, organic matter is bacterially decomposed which raises P_{CO_2} and lowers pH causing solution of carbonate which diffuses away along a concentration gradient. Simultaneously, the solubility of silica may be lowered by adsorption of organic material setting up a diffusion gradient of silica into this same region (Pittman, 1959).

Speculation

It is well known that the Edwards Group is the only cherty rock body in the Cretaceous carbonate sequence of Texas. Hence, some unique aspect or relationship must have existed within the Edwards. The Edwards Group is a carbonate body that is largely devoid of terrigenous detritus including alumino-silicate clay (Rodda, Fisher, et al., 1966). It seems likely that the diagenetic mobilization of biogenic opal into monosilicic acid is a relatively constant and common phenomenon. The mobilized silica ordinarily may be attracted to somewhat degraded clay minerals which it helps reionize or recrystallize. But if the mobilized silica is in a carbonate rock body lacking terrigenous clay nucleation centers then by default the readied silica may accrete around some other silica-containing nucleus like a sponge spicule or grain of quartz silt. Thus it may be that the paucity of terrigenous clay in the Edwards caused growth of chert nodules around other nuclei.

PLATE 7

A. Collapse breccia formed after dissolution of evaporite beds. Planar bedded, cherty, miliolid biosparite overlies interval with collapse breccia atop partly dedolomitized dolomite. Beneath a sharp silicified contact is dolomitized sparse biomicrite. See text or West Loop freeway roadcut section in appendix for detailed description. Section photographed is about 15 feet thick.

B. Photomicrograph of relict dolomite rhombs (dedolomite) in poikilotopic calcite patch. Sample from Colorado River bluff section evaporite-solution collapse-breccia interval. Maximum diameter of large rhomb is 0.07 mm.

C. Three dimensional view of Edwards chert exposed due to limestone dissolution. Photo taken in Inner Space Caverns near Georgetown. Height at front of photo is about 3-1/2 feet.

D. Chert apparently formed as a replacement of permeable burrows within a Person Formation sparse biomicrite. Erben quarry section in northeastern part of Sattler quadrangle.


B
D
chert
A
C

COLLAPSE-BRECCIAS DUE TO DISSOLUTION OF SUBJACENT EVAPORITE BEDS

Intervals where evaporites have been removed by dissolution occur at several different stratigraphic horizons within the Edwards Group. Two examples from different stratigraphic levels are well exposed at the West Loop freeway (plate 7A) and Colorado River bluff sections in the Austin area (see appendix). A generalized composite section shows the following features:

Grainstone (6 to 34 feet thick):	crossbedded to planar bedded, chert-bearing miliolid biomicrite to sorted biosparite
Collapse breccia (3 to 25 feet thick):	wedge of unsorted highly angular collapse breccia resting on very finely to finely crystalline dolomite and dedolomite; interval also contains chert, cavern-fill limestone with terra rosa, cementation-reduced megapore breccia porosity, pulverulite, and stylolitic recrystallized grainstones
Biomicrite beneath former evaporite beds - intensely altered (2 to 20 feet thick):	diagenetically altered sparse biomicrite (sometimes brecciated)-- dolomitized, dedolomitized, and silicified (both pervasive and nodular); upper contact sharp and silicified
Biomicrite and dolomite - less altered:	sparse foram-mollusc biomicrite (often heavily dolomitized); upper contact gradational

The paragenesis is interpreted as follows:

1) deposition of aragonite and/or calcite sediments;

2) penecontemporaneous dolomitization;

3) precipitation of bedded gypsum;

4) burial by carbonate sediments;

5) dissolution of gypsum by nearsurface ground water causing

6) collapse of overlying layers and

7) dedolomitization;

8) deposition of bedded grainstones;

9) silicification occurred from 4) through 8).

Interpretation of the West Loop freeway roadcut occurrence

A collapse breccia package lies between the 18th and 26th feet above the Bee Cave-Edwards contact at the West Loop freeway roadcut section (plate 7A and appendix). A similar sequence is found a little higher up in the Edwards at the Blanco-Colorado River divide section (see appendix). The sequence of events began with the deposition of aragonite and calcite sediments in the subtidal-intertidal environments. The most common pre-diagenesis lithology at the West Loop freeway roadcut is burrowed sparse foram and mollusc-fragment biomicrite deposited in a subtidal environment. The commonest pre-evaporite lithologies at the Blanco County section were intertidal flags and laminae of blue-green algal biolithites and intraclastic fine shell-fragment grainstones and wackestones.

The sediments were moderately to completely dolomitized in the supratidal environment. Dolomitization was probably the result of evaporative pumping with concomitant growth of gypsum crystals.

Gypsum continued to precipitate on intermittently flooded, ponded supratidal flats creating beds several feet thick. The gypsum may or may not have been intercalated with primary carbonate sediments.

The gypsum layers were buried by carbonate sediments whose original texture has been largely obscured during diagenesis. Some beds were evidently cemented early because sparse to packed relict fossils and intraclasts still may be recognized.

As the strandline prograded farther out on the platform the voids in the subtidal, intertidal, and supratidal sediments were filled with fresh water. Gypsum dissolution and removal by meteoric ground water caused collapse of the overlying carbonate layers through removal of subjacent support.

The evaporite solution may have taken place early as suggested by split and distorted chert that appears to have been distended while still plastic, i.e. in the Cretaceous. Alternatively, the chert may have replaced carbonate breccia fragments deformed during pre-chert collapse.

The idealized conditions for creation of dedolomite were well satisfied by the depositional and syndiagenetic setting of these horizons. Dedolomitization was accomplished near the surface by the calcium sulphate-charged ground water that had dissolved the gypsum layers.

Some original texture commonly is preserved through the transformations from aragonite-calcite to dolomite to dedolomite. Some dedolomites have identifiable fossils and describable intraclasts even though twice removed from their original mineralogy. Poikilotopic calcite (dedolomite) patches commonly contain relict zoned dolomite rhombs within them (plate 7B). After dolomite rhombs were expunged of Mg^{++} and replaced by Ca^{++} they may have served as nuclei for calcite overgrowths. Although, much of the poikilotopic calcite is clouded with inclusions and various impurities that tend to indicate a neomorphic rather than a pore filling origin.

When evaporite layers were dissolved and overlying layers collapsed the depositional surface was lowered several feet with resultant marine inundation. The ensuing sedimentation occurred in a shallow, high energy environment as shown by planar bedding (upper flow regime) and cross-bedding, good sorting of allochems, and intraclasts.

That the evaporite dissolution and consequent collapse brecciation is Cretaceous is also suggested by the nonfolded and undisturbed basal contact of the immediately superjacent grainstones. If collapse had occurred after the grainstones were deposited they should show variable attitudes.

Silicification seems to have continued throughout most of the process as the top of units underlying relict evaporite horizons are silicified, some of the chert within the collapse breccia appears to have been plastic during collapse, the interframework areas of the breccia have cherty infill, and the grainstones overlying the interval are cherty.

<u>Colorado River bluff occurrence</u>

The Kirschberg evaporite horizon, near the middle of the Edwards Group, is well exposed in the cutbank below Tom Miller dam in Austin (see Colorado River bluff section in appendix). It is a condensed section now only 25 to 30 feet thick due to solution removal of some beds. The interval consists of dedolomitized, cherty, collapse breccia and recrystallized limestone with pulverulite, terra rosa, and cavern fill. These heavily altered beds rest on leached dolomites that replaced thinly lensed, intertidal biomicrites and microcoquina.

The overall sequence of events is similar to the West Loop freeway occurrence except for the length of time between the paragenetic steps. The pronounced anticline-syncline aspect of the overlying beds shows that the major evaporite dissolution post-dated their deposition. Gypsum from this horizon is currently mined near Fredericksburg and ground water from some wells penetrating this horizon is reported to have high sulfate concentrations.

EFFECTS OF FRACTURES AND LITHOLOGY UPON POROSITY DEVELOPMENT

Near-vertical fractures

Joints have provided entryways into the Edwards Group for meteoric water. However, in the subsurface it is doubtful that joints stand open below 400 to 500 feet because of lithostatic load (L. Jan Turk, personal communication, 1973). Commonly, the fractures have been enlarged by solution but only exceptionally to the extreme proportions shown in plate 8B. More commonly the fractures vary between 1/16 to 2 inches with occasional large megapore channels or small caverns (plate 9A). Although cavernous porosity developed along fracture traces is evident within the Edwards the preponderance of porosity has been created in near-horizontal fashion along or within bedding (plate 10A) or along intersections of joints and bedding.

Many near-vertical fractures do not pass uninterrupted through thick sequences of beds; they are developed across only one or a few beds. This is corroborated by the observation that seep springs begin to flow after rainstorms. This means that much of the rain water that does sink into upland surfaces goes down short, near-vertical joints then moves along bedding partings to exit on hillsides.

Burrowed sparse biomicrite

One of the commonest pre-diagenetic lithologies within the Edwards is burrowed sparse biomicrite. The burrows ordinarily contain less micrite and more fossil fragment grains than the host rock. The higher porosity and permeability within burrows results in greater amounts of ground-water transmittance and hence larger quantities of dissolution. This process of solution enlargement develops through a sequence of commonly observed porosity types. Initially the solution creates larger interparticle pores by removing unstable aragonitic skeletal debris. The intergrain connections commonly grow into mesopore channel systems then into honeycomb porosity. As solution progresses the honeycomb pore network (i.e. cleansed burrows) loses its characteristic shape. It becomes a large megapore or cavern system whose size obliterates the moldic pores that gave rise to the void system.

The inferred sequence of porosity development within burrowed sparse biomicrites can sometimes be seen within a single small exposure. Plate 9B, and the outcrop even more obviously, shows an almost homogeneously developed porosity system. Why is porosity evolved so unequally? This may be a small scale representation of a master conduit porosity system. That is, slight and essentially undetectable primary permeability differences resulted in one or more burrows transmitting slightly greater volumes of ground water with concomitant increases in solution-enlargement. Initially slight permeability differences were continually amplified as burrows with slightly greater original permeability received ever increasing amounts of ground water. This process continued to such a degree that burrows enlarged to small caverns are found next to burrows that received only slight interparticle porosity augmentation. From an almost fortuitous start in a nearly homogeneous bed the process of master conduit development can be inferred in miniature.

Caprinid biolithite

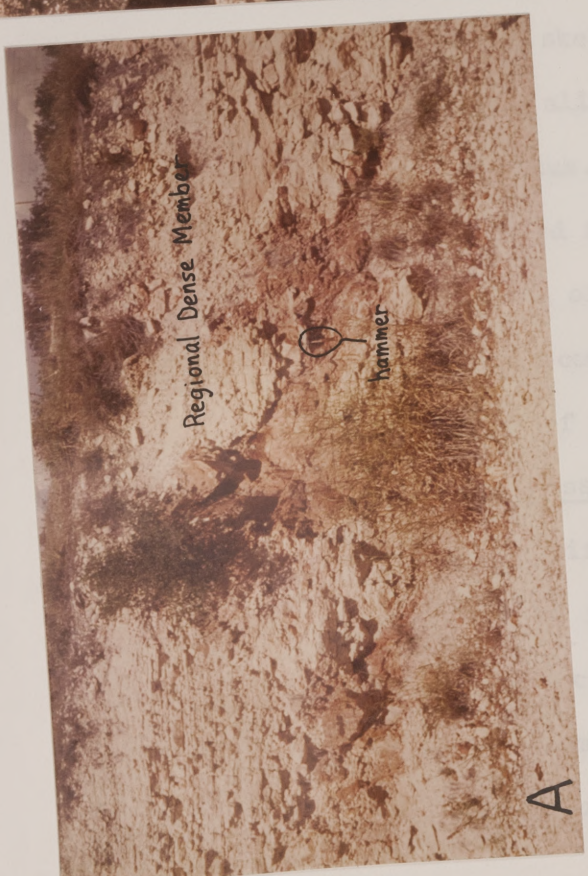
Caprinids are aberrant, thick shelled, highly inequivalved, reef

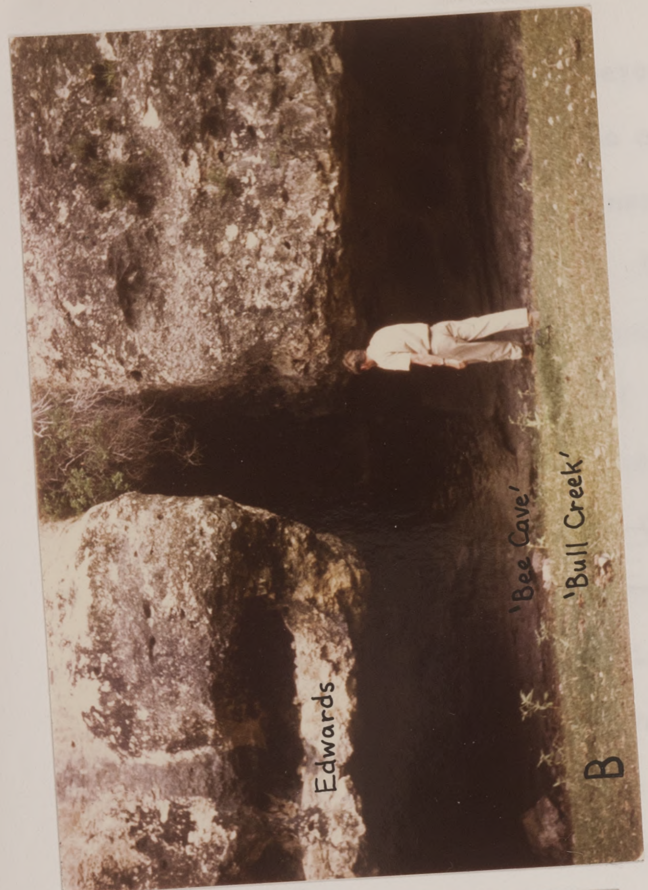
PLATE 8

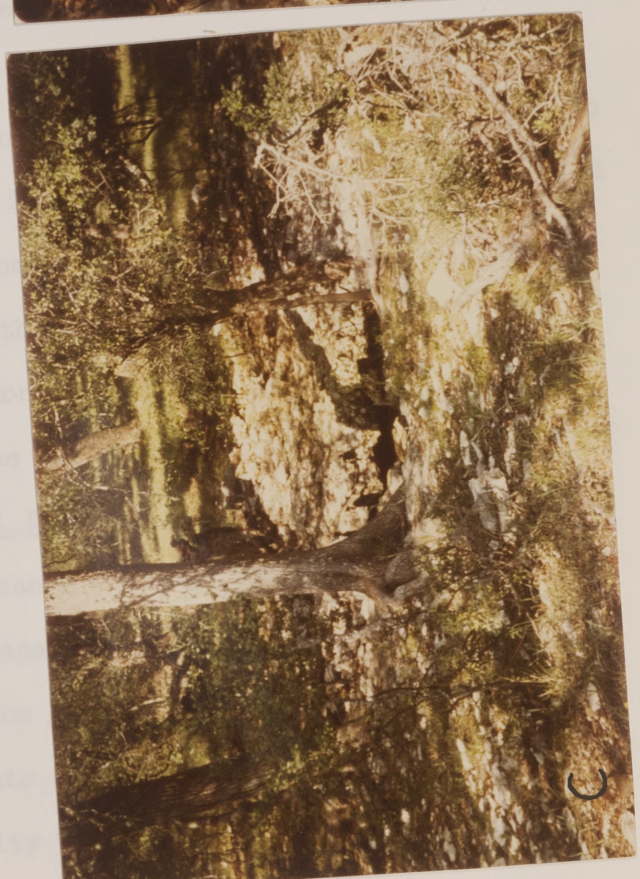
A. Former cavern cutting across the Regional Dense Member now plugged by red, extremely coarsely crystalline calcite. Roadcut along Bear Creek road about 1/2 mile north of Highway 46 in west-central top portion of New Braunfels West quadrangle.

B. Solution-enlarged joint in basal Edwards Group just above a recessive *Exogyra texana* marl of the Walnut Fm. Photographed near mouth of Isaac Creek at the 1st crossing of the Guadalupe River.

C. & D. Near vertical shaft that serves as a drain for a several acre collapse sinkhole. Mouth is about 4 feet across and the pipe drops about 60 feet before reaching first horizontal passage. Located near John Classen ranch house in southeastern corner of Bulverde quadrangle.


Regional Dense Member
hammer
A


Edwards
'Bee Cave'
'Bull Creek'
B


C


D

building pelecypods. They are several inches long with a gross shape similar to the horns of an impala or bighorn sheep. The shell apparently is constructed of an unstable mineral, probably aragonite, for what is invariably seen is a large mold. The outer wall has a sheath of micrite filled tubes, circular to subcircular in cross section and elongated parallel to the long direction of the mold. When the big (e.g. 8" long x 2" wide), open coiled moldic pores after caprinids are numerous they form large megapore channel systems. Caprinid biolithites are common in the Edwards and many of the honeycombed beds have formed from them (plate 9C). Moldic porosity after caprinids is commonly enlarged into cavernous systems in both the Edwards and Glen Rose.

Large allochem coquina

A third lithology wherein honeycomb porosity develops is shell mounds or placers of rudaceous skeletal debris. The initial high shelter and intergranular porosity allows easy movement of ground water which removes aragonitic shell detritus. The resultant meandering channels and caverns are easily distinguished from the two foregoing honeycomb porosity occurrences by examination of the undissolved host rock. Honeycomb porosity of this origin is not common in the Edwards. The best example is in the basal 25 to 50 feet of the Glen Rose Formation.

Grainstone composed of small fossil fragments

The quantitatively significant skeletal debris within the Edwards is sand to granule sized fossil fragments and miliolids. Dissolution of the aragonitic part of this fraction creates molds, vugs, and mesopore channels. When the fossil fragments occur in thin laminae their removal creates a fenestral sort of porosity usually associated with blue-green algal stromatolites. Overall porosity development is not as significant in this category as in previously described categories.

Collapse breccia

Collapse breccias resulting from loss of subjacent support due to evaporite dissolution contain large interconnected pores from their beginning. Whether of Cretaceous or Neogene origin they commonly exhibit cavern development. The distinctive features of collapse breccias associated with evaporite horizons separate them from the chaos of cavern collapse breccias.

Breccias formed from the collapse of caverns are usually interpreted as having occurred in the vadose zone (Stringfield and LeGrand, 1969). In this field area, interpretations are that as erosion lowered the land surface, with corresponding declines of the water table, some phreatic zone caverns became part of the vadose zone. Drained of support-giving ground water and as descending vadose waters sapped the roof support, collapses were fairly common.

Surface sinkholes form above collapsed areas and serve as gathering areas which funnel surface precipitation into the interclast porosity of the collapse breccia. Water migrating down through sinkholes dissolved out near-vertical shafts (plates 8C, 8D). The sinkhole and vertical shaft association works like an unstoppered bathtub unless plugged by large quantities of terrigenous clay.

Thus, the aquifer history of a sub-water table cavern, although probably reduced, is not necessarily over if its ceiling collapses after entering the vadose zone. The associated surface depression sends water down through continually enlarged vertical shafts into the collapse breccia pore system.

Bedding partings

Horizontal bedding surfaces form high permeability avenues for lateral water movement that commonly become enlarged and cavernous. These bedding separations provide egress for many of the small springs noted on the outcrop. This type of porosity is especially effective if the parting separates a lower, poorly permeable bed from an upper bed susceptible to solution. Then water moving along the horizontal separation is channeled to create maximum effective solution in the overlying stratum (plate 9D). Ground water may also move laterally through short vertical joints and pores within the rock layers.

PLATE 9

A. Solution enlarged fractures with occasional small caverns in the upper beds of the Grainstone Member of the Kainer Formation. Exposed in a McDonough Bros. quarry on Highway 281 in the west-central top portion of the Longhorn quadrangle. Quarry wall about 30 feet high.

B. Evenly distributed burrows in sparse biomicrite of the Kainer Fm. Note the porosity variations from filled burrows to partially excavated burrows to cleansed burrows to large megapore channels to small caverns. Outcrop is in Erben quarry in the northeastern part of the Sattler quadrangle.

C. Honeycomb porosity developed in moldic fashion within a caprinid bank. Some steinkerns and tubes are visible. Photographed at Bear Creek roadcut section in west-central Sattler quadrangle.

D. Cavern (3 ft. high) developed within a caprinid biolithite above a solution-enlarged bedding separation. Notice that no vertical joints intersect the cavern. Exposed on the Foster Ranch along Barton Creek in the Austin West quadrangle.


B
D
A
C
tubes
steinkerns

DRUSY ENCRUSTATION AND SECONDARY CALCITE INFILL

Megapore channel (honeycomb) porosity systems presumably develop in the phreatic zone. When the water table drops and places void networks into the vadose zone it is believed that precipitation of calcite (or dolomite, aragonite, etc.) dominates (Stringfield and LeGrand, 1969).

Meteoric water percolates down through soil and picks up additional carbon dioxide which increases its acidity. Water descending through the vadose zone with carbonic acid concentrations in equilibrium with atmospheric carbon dioxide will cause solution of carbonate rock. When calcium carbonate-saturated ground water enters a channel or cavern with lower pressure than nearby small pores some carbon dioxide escapes with a concomitant decrease in acidity. This results in calcite precipitation. The mineralization ordinarily begins with drusy encrustations and this porosity reduction by cementation commonly goes to completion. Customarily, voids are not filled in one simple episode as is indicated by calcite bands, patches of different color (clear, white, yellow, orange, red), and varying crystal sizes and shapes (plates 10B, 10C, 10D).

On hillslope outcrops the Edwards generally seems less porous than in roadcuts and quarries. This is partly due to infilling of voids by caliche which is masked by the typical gray patina which covers the Edwards outcrop.

PLATE 10

A. Solutionways and caverns are preferentially developed in certain Person Formation strata. Several former caverns are now infilled with terra rosa. Exposure in cut-face in Servtex Materials Company quarry in southeastern Bat Cave quadrangle. Section photographed is about 20 feet thick.

B. Cementation-reduced porosity in collapse breccia in Person Formation. Servtex Materials Company quarry.

C. & D. Highly dissolved lithologies within the Person Formation. Secondary calcite infill occurs as drusy encrustations. Servtex Materials Company quarry.


B
D
A
C

SOME TRADITIONAL PRINCIPLES OF CARBONATE HYDROLOGY

The study of carbonate hydrology has been closely linked with the geomorphology of karst terranes. A ruling hypothesis in this realm is the two-cycle theory of cave development proposed by William Morris Davis (1930). Davis recognized the dominance of ground-water dissolution in the phreatic zone and the importance of precipitation in the vadose zone, i.e. "caverns are produced largely by ground-water solution below the water table and then, after regional elevation, drained of their previous water-filling and on thus becoming filled with ground-air, made ready for dripstone deposition."

Ground water circulating through carbonate rock creates and enlarges an aquifer. Hydrolysis

$$(CaCO_3 + H_2O \rightleftharpoons Ca^{++} + HCO_3^- + OH^- \quad \text{where } H_2O \rightleftharpoons H^+ + OH^- \quad K=10^{-14})$$

is very slow although significant solution can be accomplished by large flows of ground water over long intervals of time. Meteoric water equilibrates with atmospheric carbon dioxide ($P_{CO_2}=3x10^{-4}$) to form carbonic acid which dissolves limestone

$$(CaCO_3 + H_2CO_3 \rightleftharpoons Ca^{++} + 2HCO_3^- \quad \text{where } H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \quad K_1=10^{-6.35})$$

much more readily.

Water that percolates down through a soil profile is exposed to carbon dioxide concentrations ($P_{CO_2}=10^{-1}$) about three orders of magnitude greater than the atmospheric value (Thrailkill, 1968). However the greater acidity of vadose seepage increases carbonate rock dissolution near the land surface such that these waters may reach the water table supersaturated with respect to calcite.

The heterogeneous void systems in carbonate rock cause ground water to produce highly anisotropic aquifers. Near vertical joints and faults and horizontal bedding separations are important permeability occurrences in carbonate rocks. The relatively homogeneous intergranular pores that typify sandstone are rivaled in number of occurrences by intragranular, intercrystalline, fenestral, moldic, collapse breccia, and other heterogeneous pore types.

The rudiments of carbonate hydrology have typically been explained by a logical analysis of the standard flow net (Rhoades and Sinacori, 1941). Ground water is shown to flow in arcuate, concave upward paths that descend beneath recharge sites and ascend toward discharge points (figure 5).

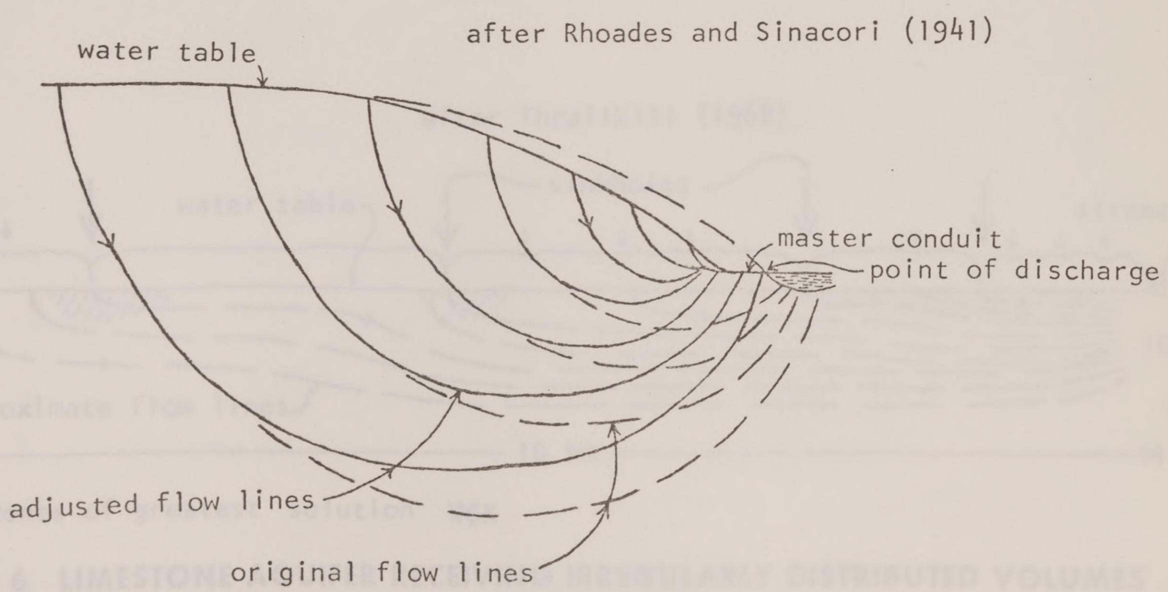


Figure 5 IDEALIZED FLOW NET AND DEVELOPMENT OF A MASTER CONDUIT

Flow tubes are depicted as moving through larger volumes of rock with increases in depth and distance from the discharge area. Since a flow tube running near the water table is passing the same volume of ground water through a markedly smaller rock volume than a deeper flow tube it would appear that the shallower flow path will receive more solution per unit volume than a longer, deeper water route. This relatively concentrated dissolution near the water table and discharge outlets creates solution-enlarged channel systems that siphon off ever increasing percentages of the ground water. A self-ramifying process is in effect as greater volumes of water flow cause greater amounts of dissolution which ultimately results in interconnected cavern systems termed master conduits by Rhoades and Sinacori (1941).

A more complex model of recharge, rock dissolution, and ground water flow in a limestone terrane is shown in figure 6.

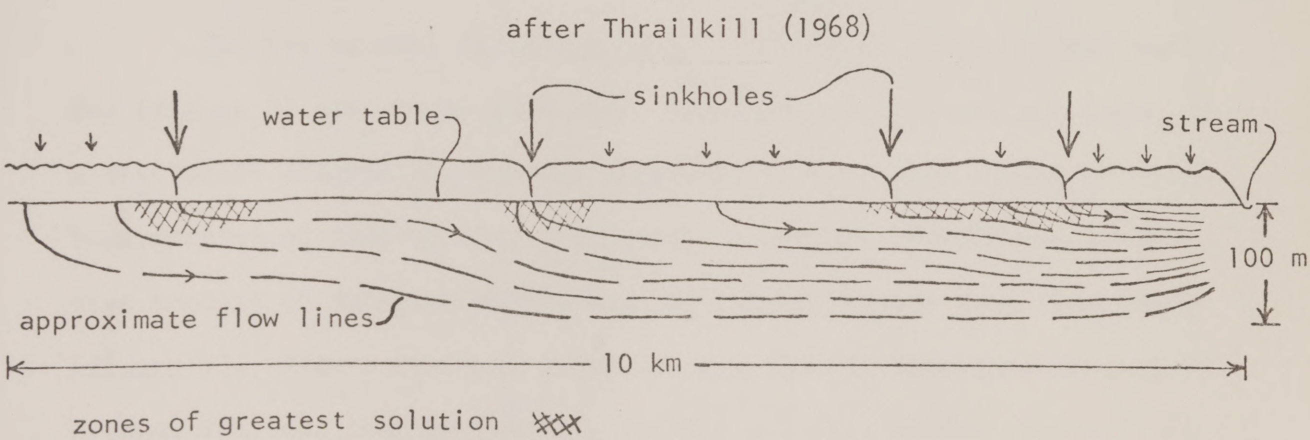


Figure 6 LIMESTONE AQUIFER RECEIVING IRREGULARLY DISTRIBUTED VOLUMES OF RECHARGE

This generalized system invokes a more realistic, irregular distribution of recharge. Meteoric water is supplied to the aquifer by local, high volume, calcite-undersaturated vadose flows and pervasive, low volume, calcite-saturated to supersaturated vadose seepage. Shallow phreatic dissolution is expected to be concentrated at vadose flow entry areas such as beneath sinkholes or swallow-holes. The undersaturated vadose flow contribution will then be deflected laterally by regional flow patterns thus tending to concentrate dissolution into somewhat horizontal channels.

SOME ASPECTS OF HYDROLOGY WITHIN THE EDWARDS LIMESTONE

The foregoing models are placed in better perspective when cross-sections of the Edwards Limestone aquifer are constructed with little or no vertical exaggeration (figure 7).

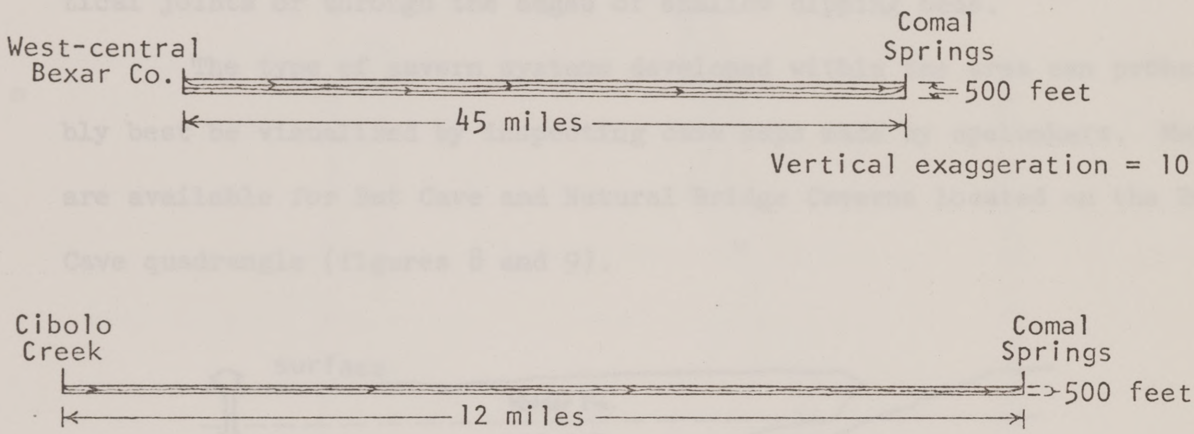


Figure 7 NEAR SCALE CROSS SECTIONS OF EDWARDS LIMESTONE AQUIFER

The few natural discharge sites from the Edwards confined aquifer (figure 3) are widely separated. Thus when flow lines are drawn on a true scale diagram the Edwards Limestone is not thick enough to allow construction of looping flow lines with consequent discussions of relative amounts of solution-enlargement in shallow versus deep flow tubes (figure 7). From a regional viewpoint the Edwards Limestone appears as a thin, faulted, near horizontal, readily soluble, bedded carbonate rock body sandwiched between less permeable rocks. The many miles between some recharge sites and the discharge outlets makes the entire Edwards Limestone in the Balcones fault zone appear like a master conduit.

Meteoric water primarily enters the Edwards Limestone as high volume vadose flows in a relatively small number of localities rather than as widespread, pervasive vadose seepage. Most of the major surface flow entryways occur in stream beds through solution-enlarged, near vertical joints or through the edges of shallow dipping beds.

The type of cavern systems developed within the area can probably best be visualized by inspecting cave maps made by spelunkers. Maps are available for Bat Cave and Natural Bridge Caverns located on the Bat Cave quadrangle (figures 8 and 9).

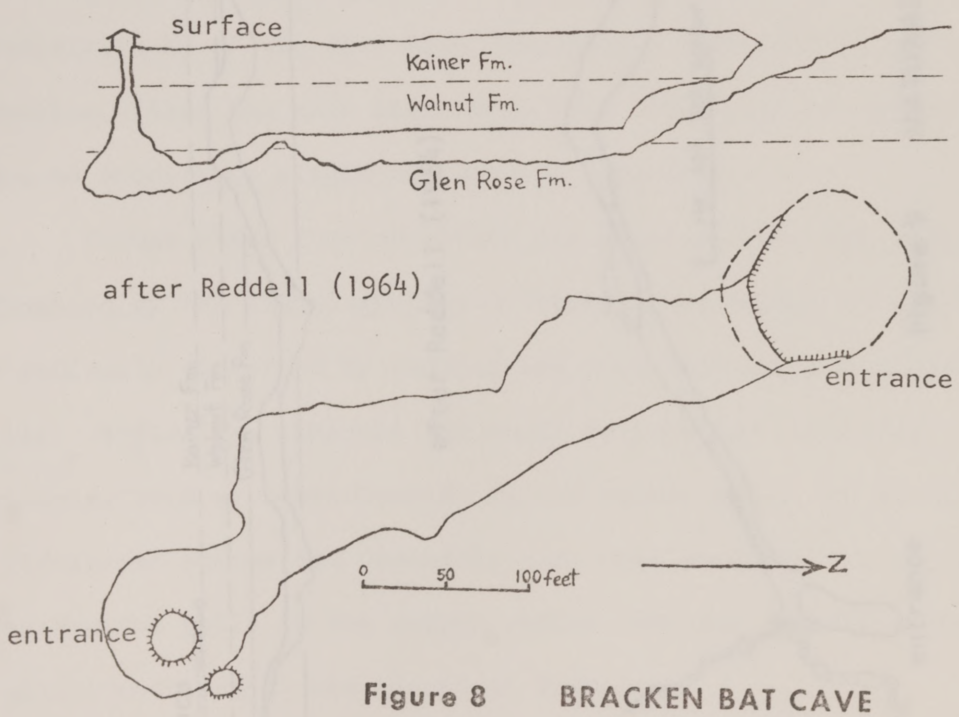


Figure 8 BRACKEN BAT CAVE

These caverns have developed in the Glen Rose Formation next to the Bat Cave fault and on its upthrown block. Although the caves have formed in

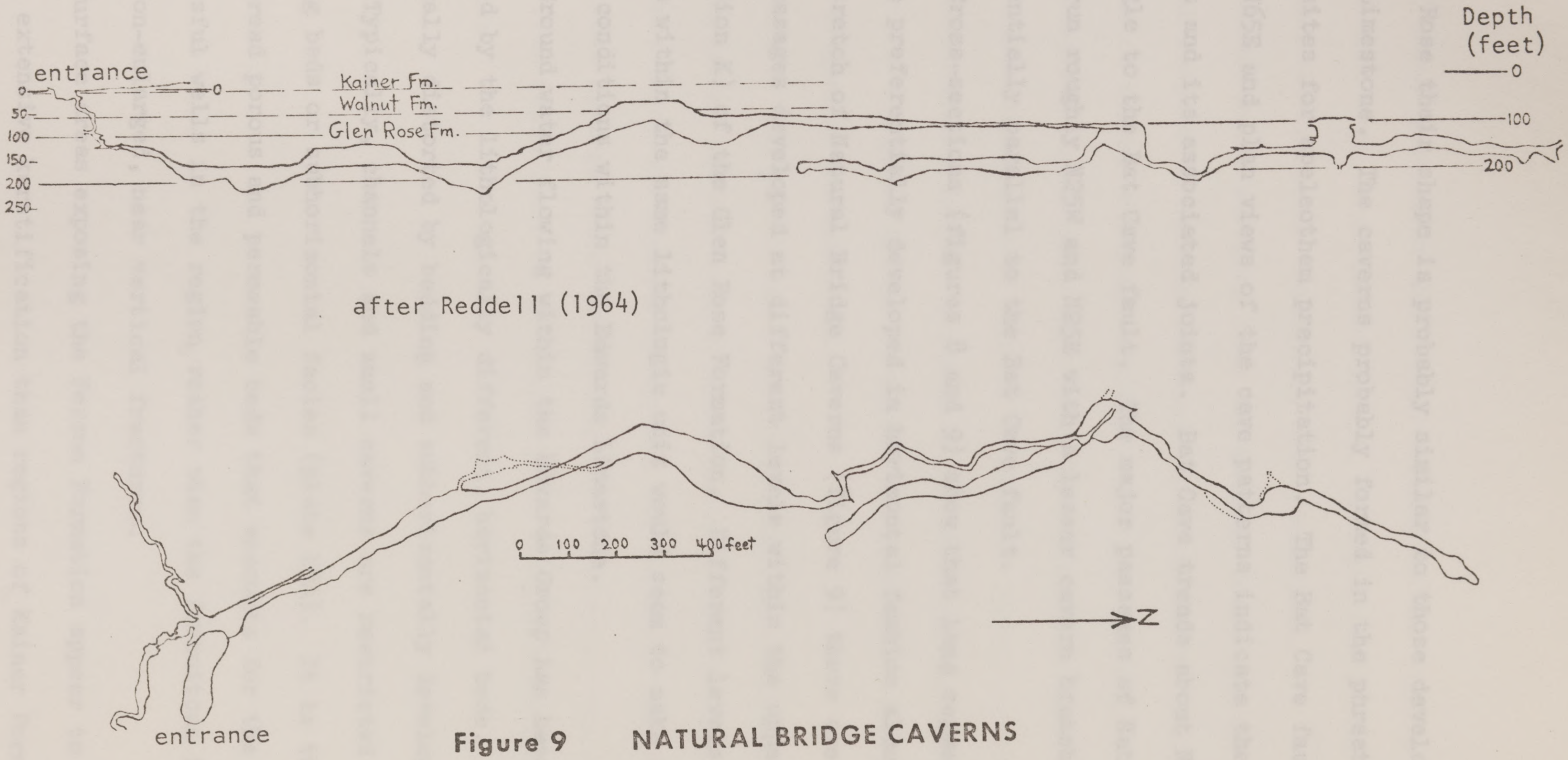


Figure 9 NATURAL BRIDGE CAVERNS

the Glen Rose their shape is probably similar to those developed in the Edwards Limestone. The caverns probably formed in the phreatic zone and are now sites for speleothem precipitation. The Bat Cave fault trends roughly N65E and plan views of the cave patterns indicate the control of the fault and its associated joints. Bat Cave trends about N25W at a right angle to the Bat Cave fault. The major passages of Natural Bridge Caverns run roughly N25W and N25E with a lesser cavern branch elongated N65E essentially parallel to the Bat Cave fault.

Cross-sections (figures 8 and 9) show that long segments of the caves are preferentially developed in horizontal fashion along bedding. In one stretch of Natural Bridge Caverns (figure 9) there are two subhorizontal passages developed at different levels within the upper dolomite (subdivision K) of the Glen Rose Formation. Different levels of cave formation within the same lithologic unit would seem to make a good analogue to conditions within the Edwards Limestone.

Ground water flowing within the Edwards Group has been markedly influenced by the lithologically different, horizontal beds. Flow lines are radically distorted by bedding and subhorizontally developed permeability. Typically, channels and small caverns are restricted to certain flat-lying beds or subhorizontal facies (plate 10A). It is the presence of widespread porous and permeable beds that accounts for the large number of successful wells in the region rather than the fortuitous intersections of solution-enlarged, near vertical fractures.

Surface areas exposing the Person Formation appear to have undergone more extensive karstification than regions of Kainer Formation outcrop. However, close inspection of measured sections and cores (see appendix) shows the Kainer and Person Formations are similar lithologically and that vugs, honeycombed strata, enlarged horizontal and vertical joints, and caverns occur throughout both formations.

Ground water emerging from the Edwards Group appears undersaturated with respect to calcium carbonate as evidenced by the lack of tufa precipitation around discharge outlets. However, analytical data of the U. S. Geological Survey show that water in the Edwards commonly is saturated or supersaturated with respect to calcite (Robert W. Maclay, personal communication, 1973). Although supersaturation is common the values evidently are not great enough to exceed the nucleation threshold necessary for aragonite precipitation.

Much of the ground water discharged through Comal Springs has moved underground several tens of miles and must have descended a few hundred feet below the surface to explain its elevated temperature. Yet even at Comal Springs where warmed water of relatively long residence time comes up from depth there is no aragonite or calcite precipitation around the outlets.

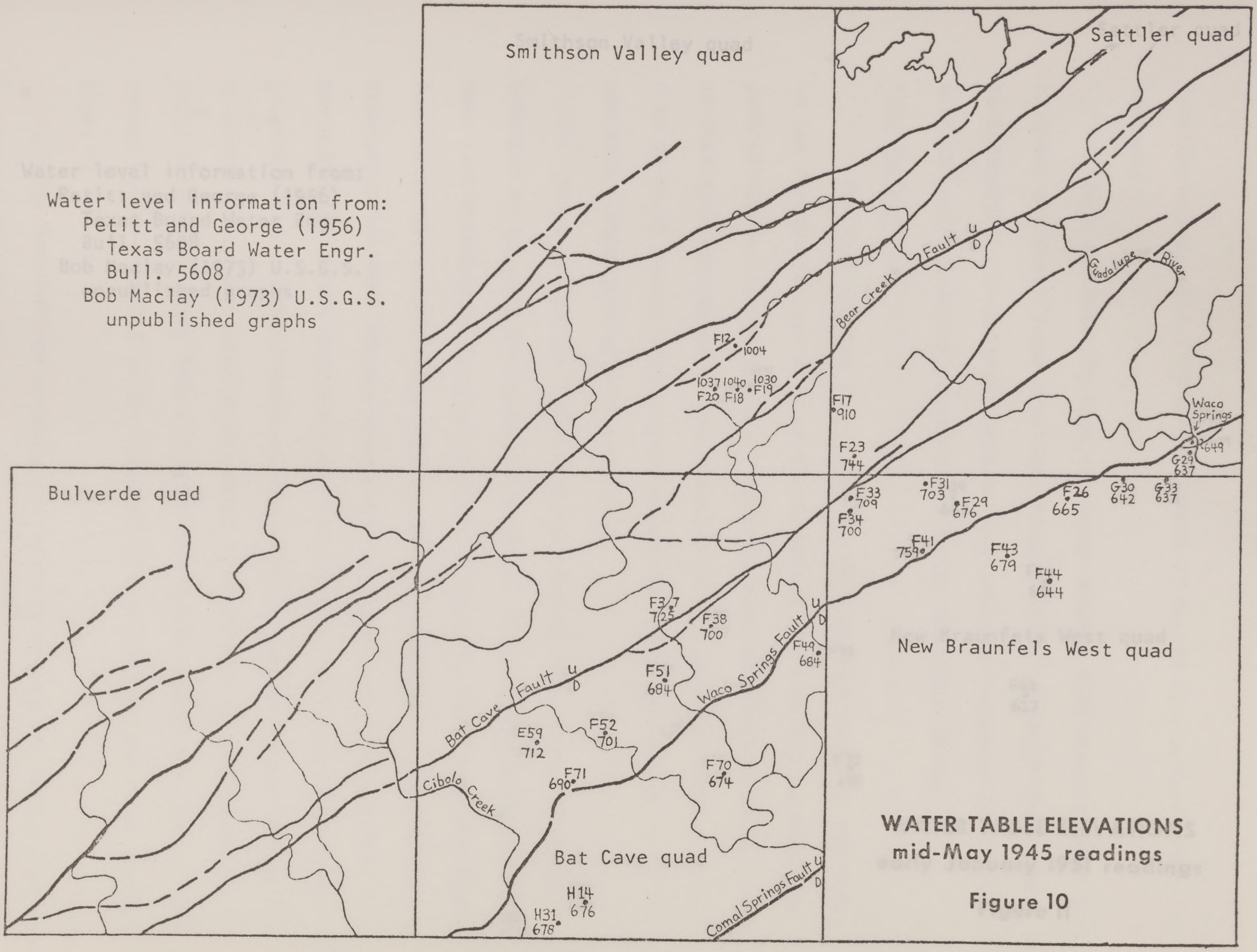
FAULT CONTROL OF GROUND-WATER FLOW

Faults commonly provide conduits for lateral water movement or they may juxtapose different aquifers so that water can move downdip across faults. In other cases the faults serve as barriers which have been instrumental in creating large discharges.

Plots of water table (static head) elevations were made (figures 10 and 11) in order to evaluate the effect of specific faults upon ground-water movement. Several books of water table elevations are available. The data consist primarily of multiple readings in the San Antonio and confined aquifer areas or of onetime water level readings in the surrounding areas. Although many wells are available for mapping the ground-water flow pattern along faults there are insufficient continuous hydrograph records and it is impossible to utilize the typical readings which were taken in widely varying months and years. Figure 10 shows a plot of water table elevations determined during a few days in May, 1945, and figure 11 plots water level readings made in early January, 1951.

The ground-water levels plotted on figures 10 and 11 do not provide sufficient data to make conclusive interpretations on the direction of ground-water movement locally. There is an overall slope of the potentiometric surface toward the southeast but this is also the direction of the regional dip. An imperfect trend of declining water table elevations to the northeast within fault blocks can be seen in figures 10 and 11. A specific program designed to measure water table elevations along and across major faults would yield additional data that might allow more

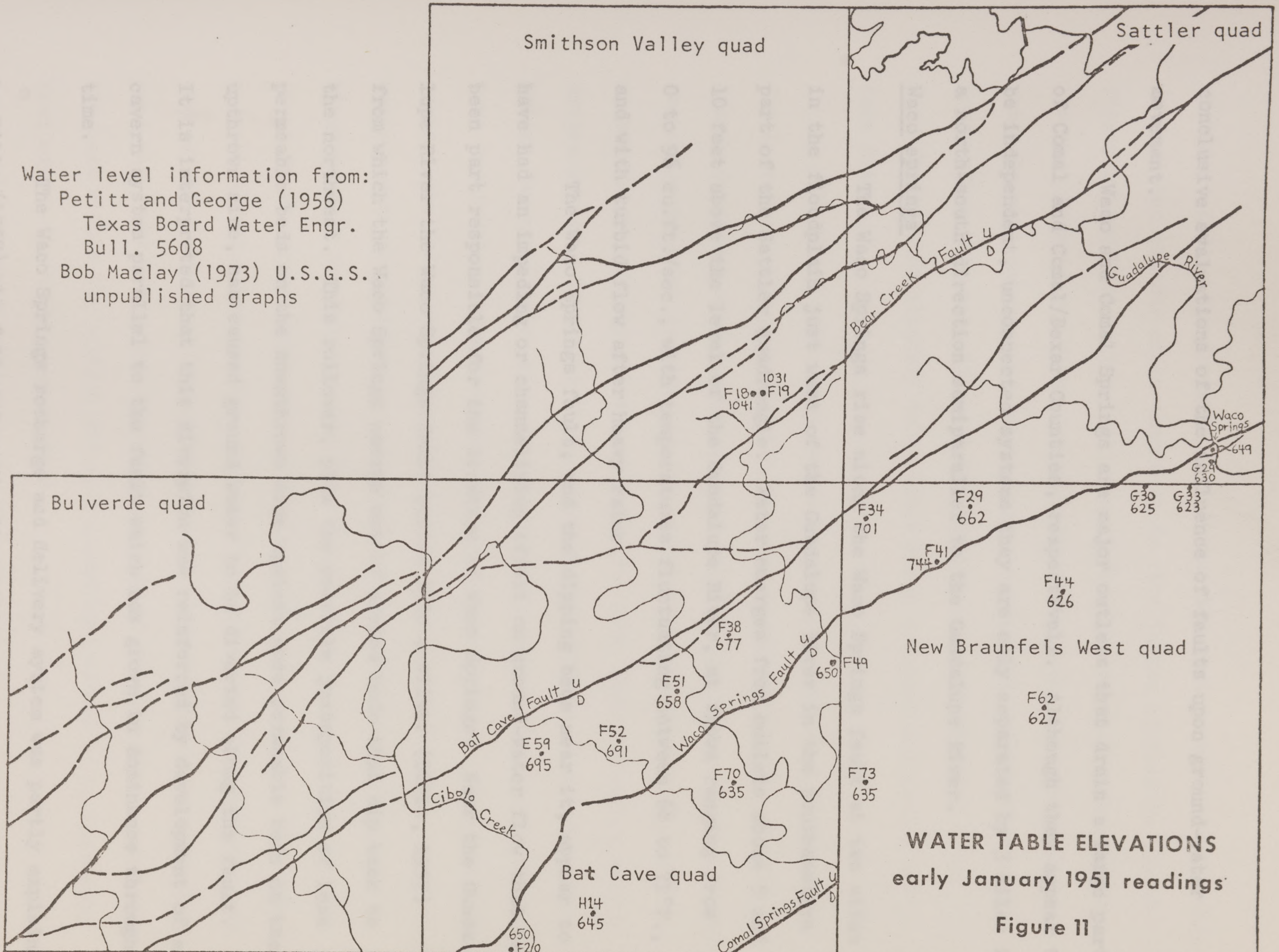
Water level information from:
Petitt and George (1956)
Texas Board Water Engr.
Bull. 5608
Bob Maclay (1973) U.S.G.S.
unpublished graphs



WATER TABLE ELEVATIONS
mid-May 1945 readings

Figure 10

Water level information from:
Petitt and George (1956)
Texas Board Water Engr.
Bull. 5608
Bob Maclay (1973) U.S.G.S.
unpublished graphs



WATER TABLE ELEVATIONS
early January 1951 readings
Figure 11

conclusive evaluations of the influence of faults upon ground-water movement.

Waco and Comal Springs are major outlets that drain a large part of Comal and Comal/Bexar Counties, respectively. Although they appear to be independent, unconnected systems they are only separated by 3 miles in a north-south direction semiparallel to the Guadalupe River.

Waco springs

The Waco Springs rise along the Waco Springs fault at two sites in the floodplain just west of the Guadalupe River in the southeastern part of the Sattler quadrangle. Water emerges from outlets about 5 and 10 feet above the level of the Guadalupe River, at flows ranging from 0 to 96 cu.ft./sec., with temperatures fluctuating between 68 to 71°F., and with turbid flow after heavy rains.

The Waco Springs fault, and the dipping beds near it, appear to have had an impeding or channelizing effect on ground-water flow that has been part responsible for the location of Waco Springs. Near the Guadalupe River the Waco Springs fault splits into a sliver (Bills, 1957) from which the Waco Springs emerge out of arched beds that dip back to the northwest. This rollover, plus the possible juxtaposition of less permeable beds on the downthrown side against more permeable beds on the upthrown side, has caused ground water to be diverted along the fault. It is interpreted that this diversion was reinforced by development of a cavern system parallel to the fault which has grown in dominance through time.

The Waco Springs recharge and delivery system was partly explained by Bills (1957) who followed up the disposition of a localized August rainstorm during the drought of 1956 when the springs were not flowing. An isolated thunder storm dumped up to five inches of rain in the vicinity of Smithson Valley. All the surface runoff went bank full down the west fork of Dry Comal Creek until reaching the Bear Creek fault where it went underground (plate 4 in rear pocket). Approximately 24 hours after this rain the west Waco Spring began discharging about 2 cu.ft./sec. of slightly muddy water which subsided and ceased two days later.

The flood water that went underground on the west fork of Dry Comal creek at the crossing with the Bear Creek fault (plate 4) most likely descended through the cover of alluvium and Walnut Formation into the upper dolomite (subdivision K) of the Glen Rose Formation. The ground water probably moved toward the Bat Cave fault through a cavern system trending S25E like the nearby Bat Cave (figure 8) and Natural Bridge Caverns (figure 9). The ground water apparently crossed the Bat Cave fault which juxtaposes the cavernous upper dolomite of the Glen Rose against the Kainer Formation (plate 11 in rear pocket). Then the ground water may have moved more or less diagonally across the narrow fault block between the Bat Cave and Waco Springs faults, passed beneath the Dietz Ranch megacollapse area, and emerged through contorted beds within a fault sliver along the Waco Springs fault to create Waco Springs. Of course the flood water that flowed down Dry Comal Creek may not be the same water which came out Waco Springs. Local flood recharge increases the head within the aquifer and the transmitted effect of an increased head may cause the springs to flow.

It is interpreted that the Waco Springs water supply system runs in large part to the east and northeast, or approximately at right angles to the surface drainage. The direction of flow is apparently subparallel to the faults and seems to illustrate the effect of the fault system on the ancient ground-water flow network. The pattern of these subsurface caverns was probably determined soon after the Guadalupe River exposed the Edwards Limestone and Waco Springs fault and opened up a discharge site. The conduit system was probably well established before the various tributary streams had cut down to near their present positions.

Comal springs

Comal Springs is a first magnitude spring whose average flow is greater than the runoff from the 1,432 square mile drainage area of the Guadalupe River above the springs. The water emerges in Landa Park in New Braunfels along a 500 yard length of the main fault-line scarp of the Balcones system (Comal Springs fault) about a mile from the Guadalupe River, which is 40 feet lower. The water is never turbid and its temperature remains steady at 74°F. which is 6° higher than the average annual temperature at New Braunfels. This increased temperature has been accounted for by circulation paths between 300 to 500 feet below the surface (George, 1948, 1952).

The immense discharge of clear, constant temperature water indicates that Comal Springs is the outlet for ground water collected over a vast area. To the north lies the effluent Guadalupe River and the isolated Waco Springs system which draws from the northwest. To the east and south is highly mineralized water from across the bad-water line. Thus the ground water must be derived from the southwest. This means the subsurface water flow is subparallel to the Balcones faults, about at right angles to the surface drainage, and at oblique angles to the regional dip and to the regional piezometric contours.

The Comal Springs fault has entirely displaced the Edwards Group in southern Comal County and caused it to abut a relatively impermeable seal of Washita Division and Gulf Series strata. Ground water migrating toward the south or east is stopped when it reaches this barrier and diverted toward the northeast along the Comal Springs fault to discharge sites opened by the downcutting of the ancestral Guadalupe River. It is hypothesized that a master conduit system, or a greater volume of honeycombed and cavernous beds, has formed parallel to the fault beneath a cover of younger rocks in analogous, and parallel, fashion to the Waco Springs system. Much of the cavernous channel system passing through Comal County to Comal Springs has been stripped of overburden and is now part of the unconfined aquifer region.

Comal Springs must derive the bulk of its water from the confined reservoir in Bexar County. The cavernous porosity system leading to Comal Springs shows some parallelism to the main Balcones fault in Comal County but the boundary of the artesian aquifer in Bexar County is apparently hydrologically controlled as it shows no direct relationship to the fault traces (compare plates 1 & 11 in Arnow, 1963).

Ancestral Comal Springs was probably established early in the history of the aquifer and at regionally low elevations due to greater incision or relatively early deep degradation of the ancestral Guadalupe River. The effect of the lower outlet elevation of Comal Springs has been felt by the ground-water body in Comal and Bexar Counties which then tended to move toward this sink. It is hypothesized that the originally subtle "feel" of a lower elevation discharge site has been made somewhat permanent through creation of a cavern and channel system that funnels ground water to Comal Springs. Both the transmitted effect of a low discharge location and the growth and piracy accomplished by headward-growing master conduits have created a circulation system whose southeastern boundary in Bexar County is hydraulically, rather than fault, controlled. The demarcation between the cavernous, high-yield aquifer and the non-cavernous, higher salinity zone occurs within fault blocks in rocks of similar depositional lithologies and is apparently a ground water bypass boundary.

BAD-WATER LINE

The southeastern boundary of the Edwards underground reservoir is a marked and mappable "bad-water line" where the total dissolved solids increases from a few hundred parts per million to greater then 1,000 ppm with a hydrogen sulfide odor. The line generally trends northeast similar to the strikes of the Balcones faults although for much of its length it does not appear fault controlled.

The U. S. Geological Survey has recently cored a hole near Randolph Air Force Base (see appendix and figure 12) that is just into the "bad-water" zone. This core appears strikingly different from the outcrop and artesian aquifer Edwards (see appendix and figure 12). The most noticeable aspect of the Randolph AFB core is its freedom from the type of meteoric water alteration commonly seen in updip rocks. The Edwards in the bad-water zone has undergone a disparate type of diagenesis. Missing are the caverns, honeycomb channel systems, solution-enlarged joints, pseudosparite beds and evident dedolomites, terra rosa, and pervasive iron oxide stains that characterize the outcrop and subsurface Edwards aquifer.

In lieu of the above items are found ubiquitous carbonaceous laminae and oil stains, a greater percentage of dolomite, gray and whitish coloration, interparticle porosity with occasional large crystals within the voids, and a dense carbonate matrix that is too fine to be accurately described with a hand lens.

The considerably different lithology of the Randolph AFB core obviously indicates a different post-depositional history. The bad-water

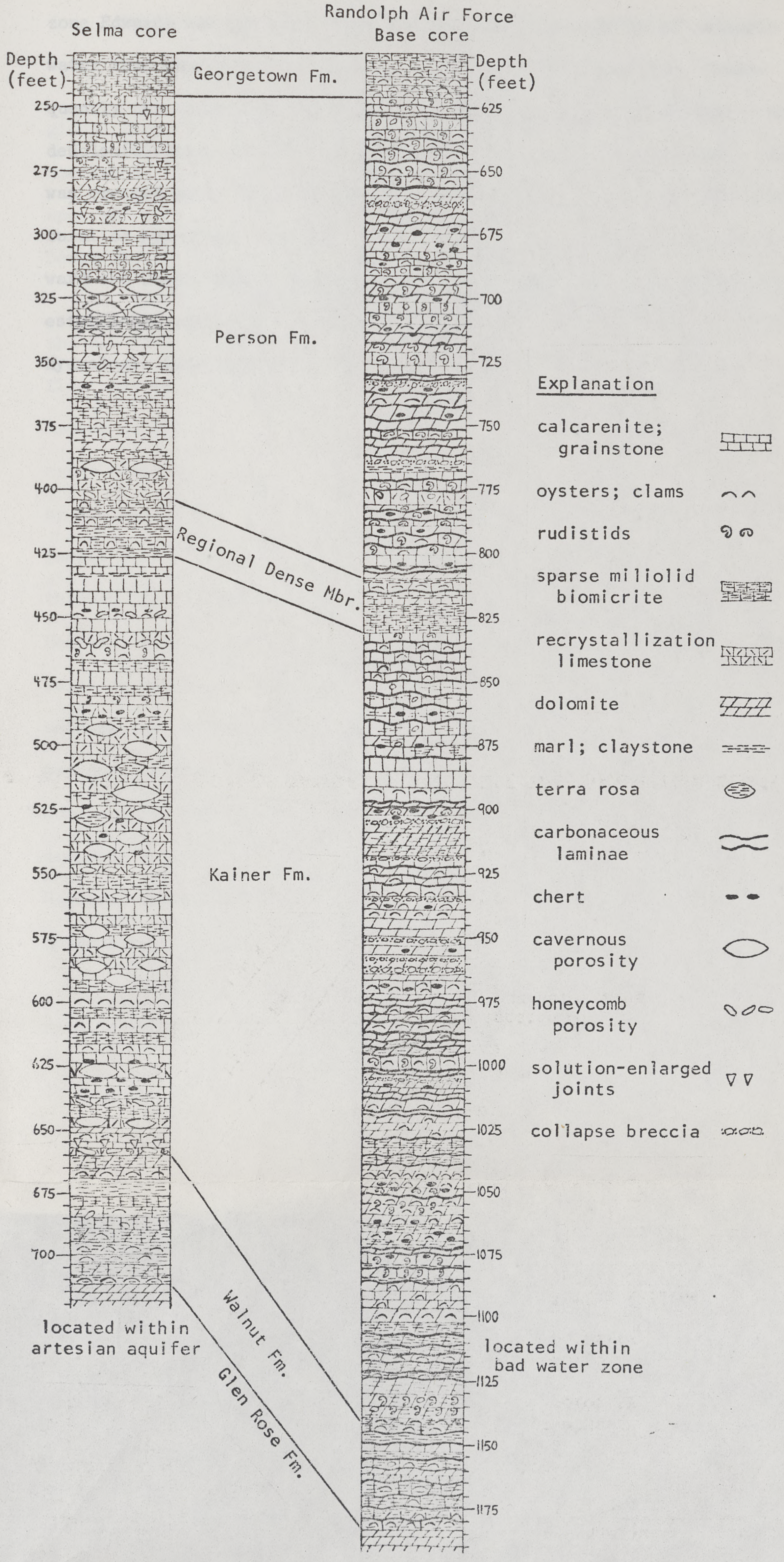


Figure 12 COMPARISON OF RANDOLPH AIR FORCE BASE AND SELMA CORES

zone Edwards has not been exposed to the large quantities of meteoric water that have moved through the adjacent artesian aquifer. Consequently the rocks lack the solution-enlargement, recrystallization, and dedolomitization characteristic of the updip rocks. The bad-water line was created as a bypass boundary that meteoric water moving under structural or hydrologic controls did not transgress. Ground water moving toward the Comal Springs sink enlarged its initial flow paths, which once established continued to grow. What originally may have been a random hydrologic flow boundary became more deeply ingrained with time.

EFFECT OF REGIONAL DENSE MEMBER ON GROUND WATER FLOW

Early in the investigation the thought was held that the Regional Dense Member might serve as a hydraulic barrier or seal separating the Kainer and Person Formations into semiseparate aquifers. However, open and infilled caverns have been observed that cut across the Regional Dense Member near the Comal Springs and Waco Springs faults.

The Barrett Industries quarry, near the southwestern corner of the Bat Cave quadrangle, uses the Regional Dense Member as a working floor in the eastern part of their pit. The overlying unit (Collapsed Member of Person Formation, Rose, 1972) is cavernous and collapsed because descending meteoric water has been ponded and diverted horizontally by the Regional Dense Member thus concentrating dissolution in the superjacent unit. The impeded or perched ground water has also enlarged joints through dissolution and created small caverns that descend through the Regional Dense Member. The quarry superintendent said that even heavy rains do not stand in ponds on the Regional Dense Member working surface because the internal drainage is so well developed. Dynamite sticks dropped down swallow holes in the Regional Dense Member blow out debris from numerous outlets in the quarry and nearby stream bed. Thus, in a rather dramatic fashion, an interconnected cavern system is shown to cross the Regional Dense Member which casts grave doubts upon its efficacy as a hydraulic barrier.

Roadcuts just north of the Waco Springs fault along Bear Creek road in the New Braunfels West quadrangle display caverns in the Regional

Dense Member that have been plugged by secondary calcite (plate 8A). When this area was below the water table, the caverns cutting across the Regional Dense Member would have connected the Person and Kainer Formations hydrologically.

Although the Regional Dense Member may not create an impassable seal it seems to create locally perched ground-water bodies which flow laterally through the immediately overlying strata. This characteristic is documented by the karstic development commonly expressed between the Waco Springs and Bat Cave faults. Within this particular fault block are a profusion of sinkholes and some mega-collapse areas.

In the southeastern part of the Bulverde quadrangle this fault block has the Regional Dense Member exposed in creek bottoms and walls whereas the interstream areas above the Regional Dense Member are dotted with plentiful sinkholes (plate 3 in pocket). Most are small dolines that are commonly used as stockponds. Some restricted tracts contain several individually noteworthy collapses within what is here termed a mega-collapse area. On the former John Classen ranch a large depression (spot elevation 983) one km. south of the southern bend of Cibolo Creek displays some erratic dips in petrified wood-bearing Person beds that have collapsed down through the Regional Dense Member. About 3/4 km. to the southeast is another large enclosed bowl that drains through a prominent vertical shaft used as a civil defense training cave (plates 8C and 8D).

Another so-called mega-collapse area is in the same fault block (i.e. bounded by Waco Springs and Bat Cave faults) in the northwestern part of the New Braunfels West quadrangle (plate 1 in pocket). The surface of this region is largely a mesquite covered, cherty, terra rosa regolith which obscures the relationships around some large collapses. On the Dietz Ranch there are Georgetown and Del Rio beds at the general stratigraphic level of the Regional Dense Member and completely surrounded by Edwards strata. This stratigraphic association, accompanied by some steep dips, suggests a downward collapse of about 200 feet.

OVERVIEW OF EDWARDS AQUIFER

A generalized geographic and chronologic picture of the Edwards aquifer is obtained by synthesizing the geologic literature with observations made during the field work for this report.

Edwards Limestone permeability provinces

A perspective view of the Edwards Limestone as a variably perforated container for fluids suggests three general provinces: 1) the Gulf coastal plain, 2) the Edwards plateau, and 3) the Balcones fault zone. This tripartite separation allows a comparison of Cretaceous versus Miocene and younger porosity development as well as an interpretation of the effect of abundant, permeable, discontinuous, near-vertical fractures.

Gulf coastal plain. Erosion before Georgetown deposition removed about 100 feet of upper Edwards (Person) along the axis of the San Marcos platform and proportionately less down the clinoforms (Rose, 1968). Accompanying the surficial erosion of Person was subsurface dissolution by Cretaceous meteoric ground water. This was superimposed on the penecontemporaneous porosity that formed during the exposures accompanying deposition of the abundant supratidal deposits.

The resultant porosity systems have become oil reservoir rocks in places such as the Fashing-Person trend in Atascosa, Karnes and Gonzales Counties. These rocks of relatively higher porosity generally lie on the upthrown sides of fault blocks where Cretaceous leaching was more intense due to greater lengths of exposure on persistent structural highs (Rose, 1968). This basinward Edwards is now buried beneath about 3,000 feet of

Upper Cretaceous and Paleocene clayey marine strata and 7,000 feet of Eocene and Oligocene paralic and fluvial terrigenous sediment. This thick blanketing sedimentary cover precluded the creation of discharge outlets, which are the prime requisite in setting up a viable ground-water circulation system. Thus the extant porosity in these oil reservoirs must be considered the product of Cretaceous meteoric water.

After examining cores from this trend, Rose (1968) described the pore systems as fine intercrystalline and intergranular porosity with fairly good permeability in leached, porous dolomite; vugs are uncommon and fractures are not enlarged by solution. Extending this porosity description along the San Marcos platform gives a rough picture of the average Cretaceous contribution to the creation of the Edwards aquifer. However, higher on the platform are pre-Dr. Burt and pre-Eagle Ford collapses indicating the existence of locally cavernous conditions in the Cretaceous (Keith Young, personal communication, 1973).

Eastern Edwards plateau. The shallow, back-reef Comanche shelf was repeatedly traversed by similar depositional environments and resultant facies. The Edwards beneath the Gulf coastal plain is lithologically and paleontologically similar to that of the eastern Edwards plateau.

The Edwards on the central part of the Comanche shelf (Central Texas platform of Rose, 1968) was interred beneath a considerably thinner Washita Division and Gulf Series section. The thinner cover on the Edwards was largely the result of shoaling and hiatuses following deposition of the Eagle Ford, Austin, and Taylor. The Edwards plateau has been above sea level since the Late Cretaceous.

As erosion progressed through the Tertiary streams cut through the

Washita-Gulf blanket and reached the Edwards as a result of uplift accompanying Balcones faulting in the Miocene. Porosity and permeability have developed through utilization and solution-enlargement of primary intergranular voids, loosely filled burrows, joints, and bedding partings. Penecontemporaneous sea water and/or later ground water has leached gypsum layers to create porous collapse breccias and remove aragonite fossils. The aforementioned pore types have been locally enlarged into vugs, channels and caverns.

Presently, some of the rain falling on central Texas seeps into the Edwards Limestone and emerges as springs where canyons have cut down to the water table and/or the base of the Edwards Limestone. Significant withdrawals are made by water wells but the yields are generally only enough to supply the sparse population of people and large population of livestock. Typical yields from the Edwards on the plateau are about 2 to 15 gallons per minute with occasional larger wells yielding several tens of gallons per minute. Springs discharging into canyons cut below the Edwards (i.e. where the aquifer ends) have flows up to 2nd and 3rd magnitude (10-100 and 1-10 cu.ft./sec. respectively) in the Meinzer (1923) classification.

Balcones fault zone. Of especial interest is the faulted Edwards Limestone confined beneath the western margin of the Gulf coastal plain. The depositional facies of the Edwards are similar to those found in the Fashing-Person trend beneath the Gulf coastal plain and on the eastern Edwards plateau. Yet the Edwards here commonly yields in excess of 1,000 gallons per minute to water wells and several large springs exist. Comal and San Marcos Springs are both of 1st magnitude (greater then 100 ft^3/sec) and other springs of 2nd magnitude (10-100 ft^3/sec) are fairly common (figure 3). These high yields exist only in this fractured belt and thus demonstrate the significance of faulting and associated permeable joints in the development of the aquifer. Surface water has used these discontinuous, near vertical fractures as avenues of access for solutional attack upon the entire Edwards section.

Geologic history of Edwards underground reservoir

Cretaceous porosity. The Cretaceous syndepositional porosity and permeability within the Edwards Limestone consisted largely of intergranular voids within skeletal grainstones and loosely packed burrows in biomicrites; intraparticle voids within bioclastic grains and shelter porosity beneath them; intercrystalline interstices in supratidal dolomites created by evaporative pumping; shrinkage cracks; fenestral openings after the blue-green algae in stromatolite biolithites; growth-framework voids in rudist biostromes and bioherms; some of the moldic pores after aragonite fossils; and breccia porosity from collapsed layers overlying dissolved supratidal evaporite beds.

Primary permeability and porosity was enlarged through solution by meteoric water supplied during the time the Edwards was being eroded and before Georgetown deposition commenced. Rose (1968) discussed an erosional vacuity of 100 feet of Person along the axis of the San Marcos platform. Erosion of this magnitude in a low relief carbonate terrane should be accompanied by large-scale karstification and dissolution concentrated in the upper beds or Person Formation (figure 13A). However, reports of Cretaceous karst are scarce. One occurrence is east of Kerrville where the Dr. Burt Member has apparently collapsed into the Kainer

Formation (Keith Young, personal communication, 1972).

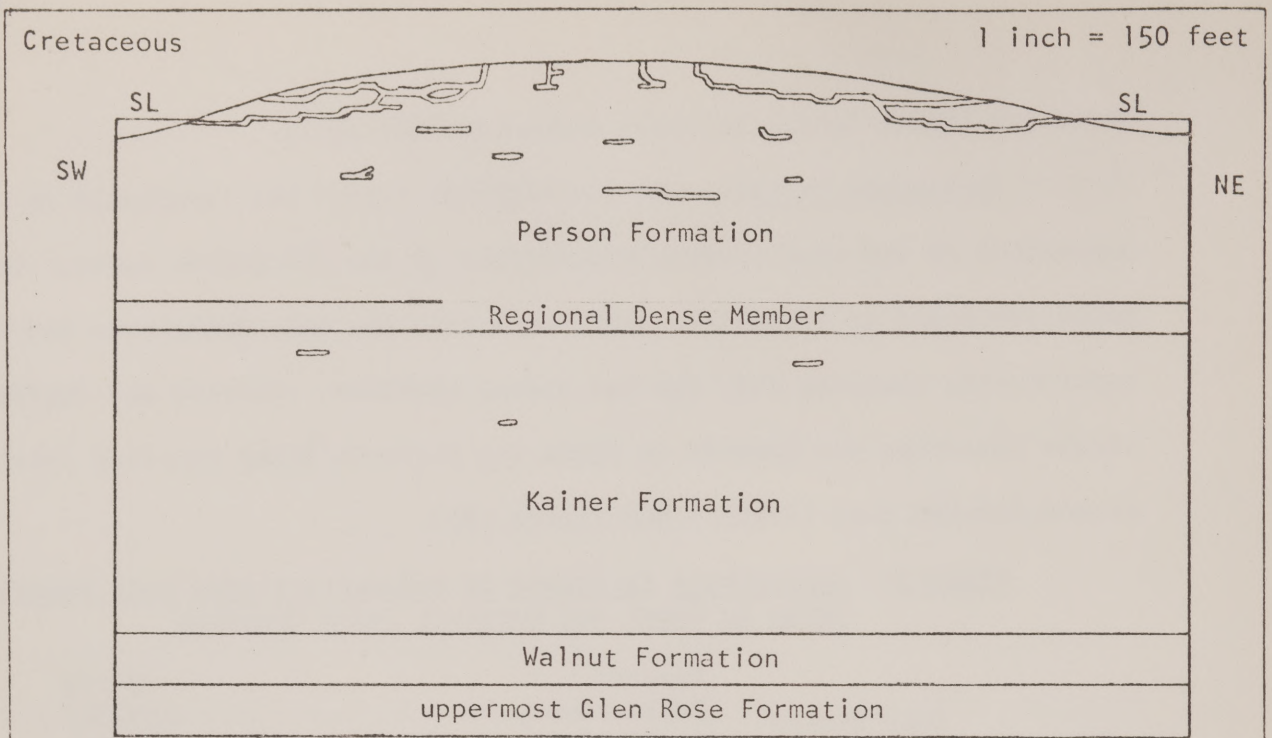
Cretaceous burial. The post-Edwards lacuna was terminated as deposition of the argillaceous biomicrites of the Georgetown began. Sediments continued to accumulate until well into the Late Cretaceous and with considerable thinning over the San Marcos platform. Washita and Gulfian strata interring the Edwards in Comal and northern Bexar Counties totalled around 500-850 feet (Table 3 and figure 13B).

Table 3. Approximate thickness of sedimentary seal over Edwards Group in Comal and northern Bexar Counties

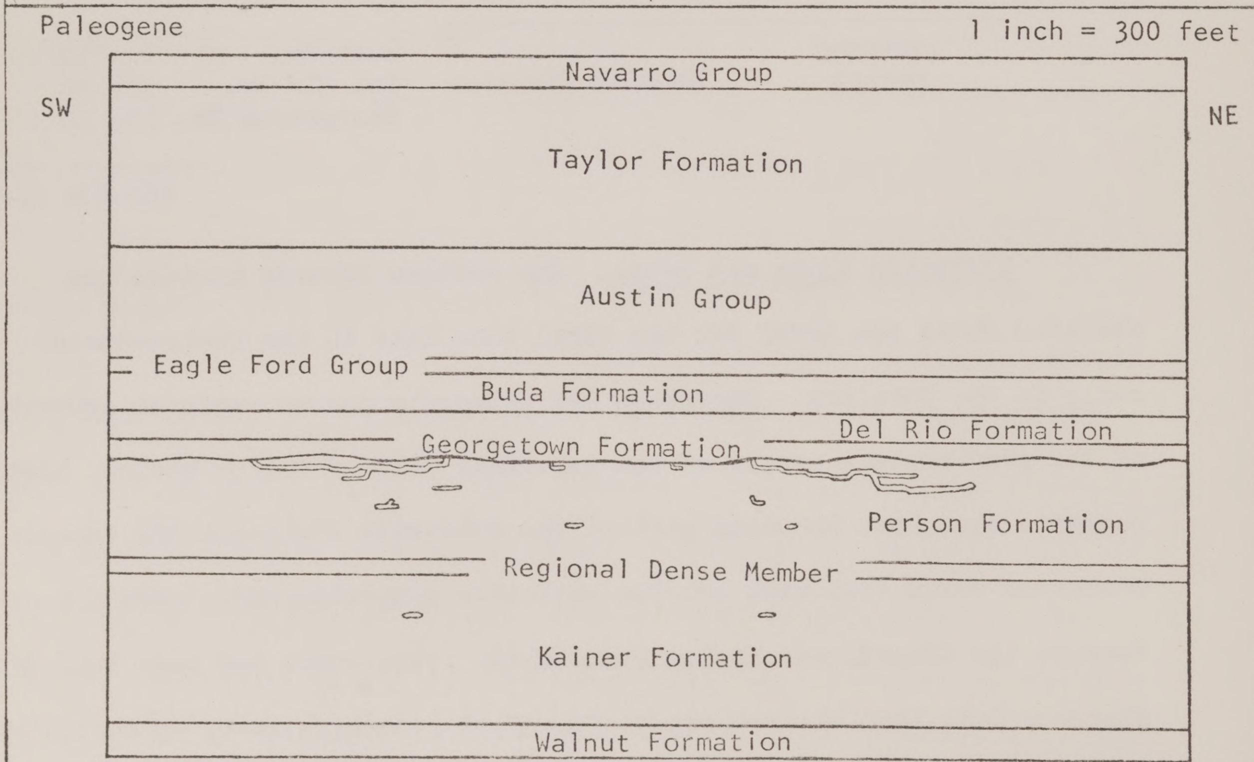
Gulf Series	Navarro		45-150
	Taylor Group		200-310
	Austin Group		140-210
	Eagle Ford Group		15- 25
Comanche Series	Washita Division	Buda Fm.	50- 70
		Del Rio Fm.	35- 55
		Georgetown Fm.	15- 30
			500-850 feet

Elevation above sea level. The eastern Edwards plateau was elevated above sea level for the final time late in the Cretaceous or early in the Tertiary. Emergence was primarily due to regional upwarping of the northwestern margin of the subsiding Gulf of Mexico basin. Logic suggests that upon becoming part of the subaerial continent the Edwards Limestone would fill with calcium carbonate undersaturated, meteoric water. Because the Edwards was buried every where there would not have been discharge points that allowed establishment of a through-going water system. Thus the ground water probably equilibrated with the rock and accomplished minimal dissolution.

Fault movements along the Balcones system. The Oakville Sandstone

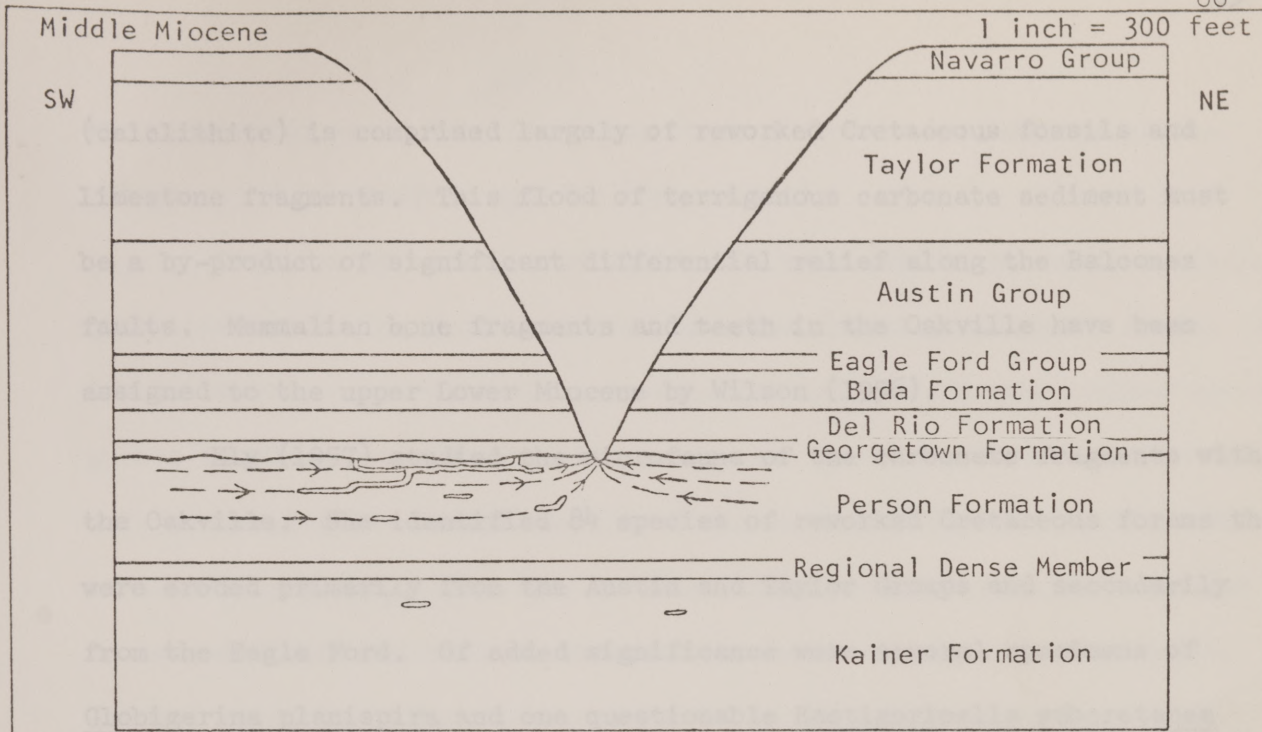


A. Subaerial exposure and erosion after deposition of Edwards Group. Subsurface dissolution most pronounced in Person Formation.

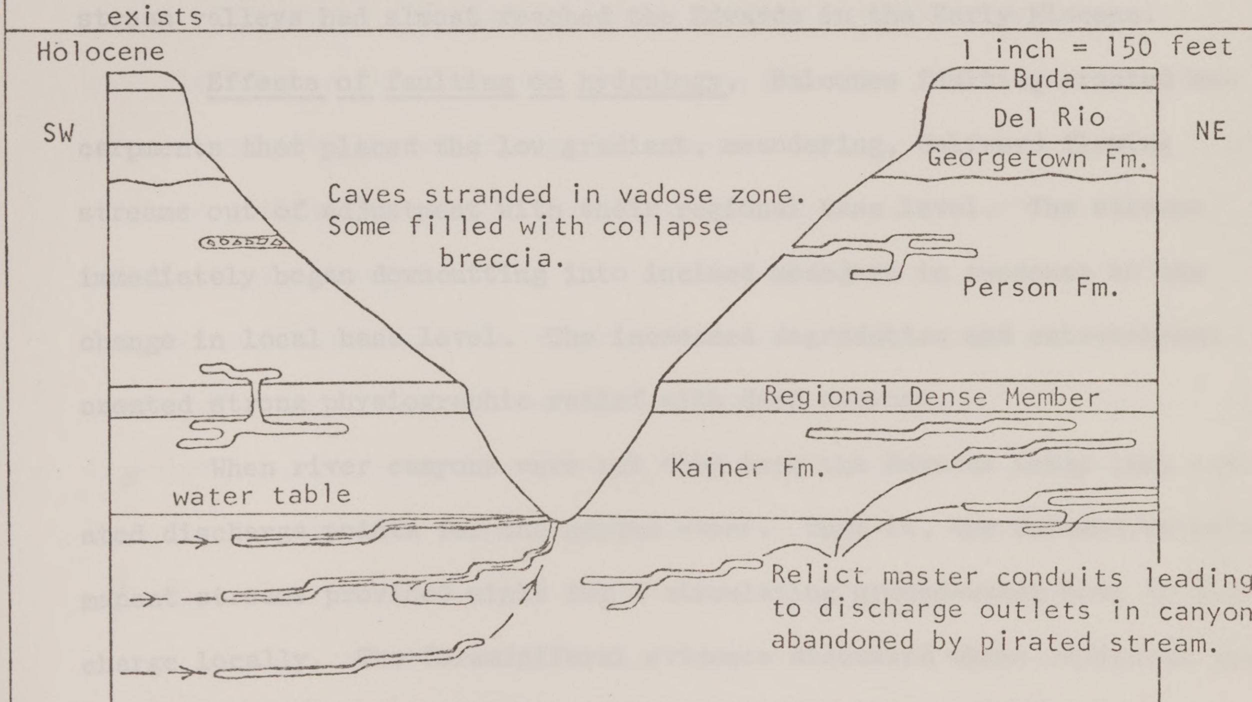


B. Edwards Group buried by about 625 feet of Washita Division and Gulf Series strata. Absence of discharge outlets precludes additional significant solution.

Figure 13. SCHEMATIC CROSS



C. Earliest outlets from Edwards underground reservoir were created when top of Person Fm. was reached by downcutting streams rejuvenated by Balcones faulting. Ground-water exiting through early discharge points solution enlarged its flowpaths in primary and secondary pore spaces, including Cretaceous Karstification, to create a pattern which still exists



D. Active discharge outlets created where modern drainage downcut and intercepted old master conduits leading to former discharge sites in abandoned stream canyon.

SECTIONS WITHIN COMAL COUNTY

(calclithite) is comprised largely of reworked Cretaceous fossils and limestone fragments. This flood of terrigenous carbonate sediment must be a by-product of significant differential relief along the Balcones faults. Mammalian bone fragments and teeth in the Oakville have been assigned to the upper Lower Miocene by Wilson (1956).

Ely (1957) studied the microfauna of the carbonate fragments within the Oakville. She identified 84 species of reworked Cretaceous forams that were eroded primarily from the Austin and Taylor Groups and secondarily from the Eagle Ford. Of added significance were several specimens of *Globigerina planispira* and one questionable *Hastigerinella subcretacea* from the Duck Creek Formation (Georgetown). The presence of Georgetown forams is important because they indicate that the most deeply incised stream valleys had almost reached the Edwards in the Early Miocene.

Effects of faulting on hydrology. Balcones faulting created escarpments that placed the low gradient, meandering, Gulfward flowing streams out of adjustment with their regional base level. The streams immediately began downcutting into incised meanders in response to the change in local base level. The increased degradation and entrenchment created strong physiographic relief with deep canyons.

When river canyons were cut down into the Edwards Group they created discharge points for the ground water. That is, the entrenched permanent streams provided sinks for a circulating ground-water body to discharge locally. The foraminiferal evidence discussed above indicates that stream canyons had already begun to reach the base of the Georgetown in the Early Miocene. Thus it seems probable that the top of the Person Formation became exposed on canyon floors later in the Miocene, possibly in the Middle Miocene. This is an important factor in the history of development of the Edwards aquifer (figure 13C).

Creation of a cavernous aquifer in carbonate rocks requires large quantities of moving ground water. Balcones faulting created a system of discontinuous, near vertical, permeable joints that allowed surface water access to the buried Edwards Limestone. As the Gulfward flowing streams cut deeply into the eastern margin of the ancestral Edwards plateau some of these fractures, along with bedding partings and strata, were exposed on canyon floors and walls. Ground water moved through these permeable lateral conduits to the discharge points in the canyon bottoms. Movement was preferentially toward these discharge areas rather than down the structural dip.

Continuous circulation system. With initial establishment of some discharge sites there was set in motion a through-flowing ground-water system which grew in significance. No matter how fortuitously the original outlets or sinks in the Person Formation were located they received the greatest amount of ground water flow, which also means they had the most solution-enlargement that in turn funneled an ever increasing amount of ground water through these exits with a concomitant increase in dissolution, etc. Through the self-ramifying pattern of ground-water circulation in carbonate rocks the locations of many master conduits were probably established early in the history of the Edwards aquifer.

Master conduits possibly may grow headward and pirate the flow of other large conduits in analogous fashion to piracy among surface streams. The concept of master conduit capture or piracy helps explain why today only a few really large springs issue from the Edwards underground reservoir. For instance, the copious discharge of and large geographic area drained by Comal Springs can be visualized as the result of master conduit piracy. Comal Springs issue forth at about 620 feet elevation, creating a low base level that affects hundreds of square miles. This was probably an early local master conduit that progressively captured more local master conduits by headward solution from its favored discharge elevation.

Neogene history. Cavernous porosity and permeability within the Edwards underground reservoir beneath the western margin of the Gulf coastal plain has continuously increased (figure 13D).

On the eastern Edwards plateau many of the strata overlying the Edwards Limestone have been stripped off. At the same time, the smaller tributary streams cut down to lower elevations thus acting in concert to lower the water table. As the phreatic surface dropped many of the master conduits were drained of ground-water and filled with the ground-air of the vadose zone. Bat Cave and Natural Bridge Caverns are examples of phreatic zone caverns now hosting speleothem precipitation in the vadose zone. As the water table declined and withdrew its support, and vadose seepage weakened ceiling strength, many caverns collapsed.

Much of the unroofing of master conduits and exposure as caves with surface entrances evidently occurred late in the Pleistocene as judged from vertebrate remains. The oldest fossils that have been found and dated are Sangamon skeletal parts from a cave in an abandoned Edwards Limestone quarry in northwest Austin (E. L. Lundelius, personal communication, 1972). The bulk of cave faunas are of Wisconsin or Holocene age thus showing the recency of exposure of the Edwards Limestone on the interstream areas of the eastern Edwards plateau.

Enumeration of factors involved in development of Edwards aquifer

Herein follows a checklist of some parameters pertinent to the Edwards aquifer.

Primary porosity. Voids were present in many depositional units within the framework of rudist biolithites, between the allochems in burrows and bioclastic grainstones, within collapse breccias, and the sundry occurrences in tidal flat deposits (e.g. moldic after salt crystals, shrinkage, fenestral after stromatolites).

Solubility of rocks. The Edwards is a mass of limestone with dolomite, chert nodules, and some evaporites, but it is largely free of terrigenous sediment. A thick sequence of relatively pure carbonate rock is most amenable to dissolution and cavern development.

Paleokarst and secondary porosity. An erosional episode followed Edwards deposition. Up to 100 feet of upper Edwards is missing along the San Marcos platform. Porosity increased through solution-enlargement of primary pores, removal of many aragonite fossils, creation of vugs and channels, and some large-scale karstification especially in the surface and nearsurface Person Formation.

Stratigraphic relations. The relatively pure and soluble Edwards Limestone is sandwiched between clayey biomicrites, marls, dolomites, claystones, and other less soluble rocks. It is underlain by the marls and sandy pseudosparites of the Walnut Formation which in turn overlie the dolomitized limestones and marls of the Glen Rose Formation. Overlying the Edwards are the argillaceous biomicrites of the Georgetown Formation and the Del Rio Claystone.

Faults and associated fracture systems. The high angle, en echelon, down-to-the-coast, normal faults of the Balcones system, with its associated horde of fractures, created a myriad of discontinuous, high permeability avenues for meteoric water to enter the Edwards Limestone. The resultant uplift of the Edwards plateau placed streams out of equilibrium with oceanic base level. The ensuing degradation of the eastern Edwards plateau created steep topography and exposed the fractured Edwards Limestone in canyon bottoms.

Circulation system. There are three requisite parts of a circulation system: 1) an area of intake, 2) permeability for transmission of water, and 3) outlets for discharge. The interconnected pore spaces necessary for water movement existed as primary porosity, secondary porosity associated with the Edwards-Georgetown unconformity, and the fracture fabric of the Balcones system. The area of intake was created when the Edwards plateau was upwarped above sea level. The last requisite to be fulfilled was the need for discharge sites. This was satisfied when Balcones fault-induced erosion exposed the Person Formation in entrenched stream canyons.

Base level. Stream incision of the Edwards plateau is largely due to the effect of oceanic base level on the fault-lifted plateau. However in the solutional development of the Edwards aquifer the major base level control is that of the perennial gaining streams. That is, discharge zones are created where stream canyons intersect faults, permeable strata and bedding partings. Ground water flows toward the discharge sites and dissolution enlarges the flowpaths into cavern networks.

Ground-water flow patterns. Ground water in the Edwards Limestone flows in severely flattened loops from recharge areas to discharge points. The amount of dissolution is roughly proportional to the volume of calcite-undersaturated ground water. The zone of greatest flow typically is thought to lie just beneath the water table where the more active solution creates master conduits which capture increasingly larger amounts of ground-water flow. The areal extent of the Edwards Limestone aquifer is so great compared to its thickness that the concept of increased flow and solution beneath the water table is not too meaningful. Cavernous porosity is developed throughout the Edwards Limestone.

Sinkholes and vertical shafts are generally considered to be products of dissolution in the vadose zone. Sinkholes probably form by cavern collapse and vertical shafts by downward percolation of water along joint intersections or collapse breccia filled pipes.

These concepts fit harmoniously with outcrop and subcrop observations of the Edwards Limestone.

Chemical character of recharge water. The meteoric water that enters the Edwards Limestone is mostly as vadose flows undersaturated with respect to calcite and dolomite. Only a slight undersaturation is necessary for cave excavation and this condition is enhanced in the shallow phreatic zone by the mixing of dissimilar waters and the flowrate effect (Thrailkill, 1968). The mixing mechanism is a significant source of undersaturation when small amounts of high P_{CO_2} vadose seepage are added to a low P_{CO_2} ground-water body like that in the Edwards Limestone. Increased undersaturation is also achieved when low ionic strength flood water is poured into the aquifer as is common in south-central Texas.

Presence of soil cover. Water that percolates down through a soil profile is exposed to carbon dioxide concentrations ($P_{CO_2}=10^{-1}$) about three orders of magnitude greater than the atmospheric value (Thrailkill, 1968). However the greater acidity of vadose seepage increases carbonate rock dissolution near the land surface such that these waters may reach the water table supersaturated with respect to calcite.

Rain falling on the Edwards plateau does not receive significant carbon dioxide by passing through the sparse, poorly developed soils. Percolation through the soil and entry into the phreatic zone as vadose seepage is not significant. Most recharge occurs through swallow holes in streams as low P_{CO_2} vadose flows.

Rate of ground-water circulation. The lack of tufa, dripstone, or other precipitated forms of calcium carbonate around spring orifices suggests that ground water does not reside within the aquifer long enough to equilibrate with the carbonate rock host. However, U. S. Geological Survey data show that the ground water is commonly saturated or supersaturated although the concentrations evidently do not exceed the nucleation threshold values necessary for aragonite precipitation (Robert W. Maclay, personal communication, 1973).

Volume of solvent. Greater volumes of solvent dissolve greater amounts of carbonate rock, which can in turn accept larger amounts of recharge or solvent, etc. Thus the volume of solvent and sum of solution in the Edwards aquifer has increased through time with a possible maximum rate of increase during the pluvial rains of the Pleistocene.

Temperature of ground water. Ground water temperature is approximately the same as average annual surface temperature. The warmer the water the more volatile the carbon dioxide and hence the lesser the carbonic acid concentration. At those times of year when vadose seepage is cooled at the water table significant carbonate rock dissolution should occur (Thrailkill, 1968). Cave excavation may result with temperature fluctuations as low as one degree especially if the system is open to a carbon dioxide concentration equivalent to the atmosphere.

Presumably the pluvial rains of the Pleistocene ice ages were colder and could thus contain relatively higher carbonic acid percentages that made them more effective solvents.

Kinetics. The thermodynamics of solution and precipitation thresholds indicate that more carbonate rock may be dissolved during short periods of undersaturation than would be precipitated during longer intervals of supersaturation (Thrailkill, 1968).

APPENDIX

Measured section and core descriptions

SELMA CORE

U. S. Army Corps Engineers cored a hole 1 mile northwest of Selma, Bexar Co., Texas. Core now reposes in the Well Sample Library, Room 18b, Balcones Research Center, Univ. Texas at Austin.

Depth (feet)

175-229 DEL RIO FM.

GEORGETOWN FM.

229-246 Argillaceous sparse whole mollusc biomicrite: large oysters, snails, clams and brachiopods including Kingena, Pecten, Gryphaea in tan finely fragmented biomicrite matrix; 1-2% porosity with negligible permeability is in marked contrast to subjacent Edwards and its well developed solution-enlarged moldic porosity after fossils and joints, caverns, recrystallization limestone, and speleothems.

EDWARDS GROUP

PERSON FM.

246-268 Unsorted caprinid biosparite (with some microsparite): milky white to light tan; numerous caprinids, oysters, snails and fossil fragments; good porosity-- moldic after fossils, intercrystalline, vugs to 2" diameter, and slightly enlarged joints; other features:
--at 254: 6" x 1.5" cavity after caprinid
--at 264.5: highly porous mass of fossil fragments
--at 261-268: finely crystalline calcite with voracious pinpoint porosity alternates with caprinid biosparite

268-269.5 No core

269.5-278 Clayey, burrowed sparse biomicrite: milky white to beige; burrows filled with fine fossil debris; porous-- some fractures and vugs; other features:
--at 272-273: moldic porosity after caprinids

278-287.5 Dolomitic, sparse foram-fossil fragment biomicrite and microsparite with honeycombing and secondary calcite; other features:
--at 278-281: brown, dense dolomite and recrystallization limestone with relict oysters and other fossils.
--at 281-287.5: original dolomitic biomicrite extensively dissolved to channel megapores with secondary calcite and terra rosa infill.

287.5-296 Dolomitic rudistid biomicrite and microsparite: whitish-gray: fair to good porosity-- moldic after large fossils, slightly enlarged joints, some pinpoint and honeycomb; Toucasia, caprinids, oyster and other fossil fragments; other features:
--at 288, 295: Toucasia
--at 290: dark gray chert nodules

296-299 No core

299-307.5 Fossil fragment-miliolid biomicrite & biosparite: packed miliolid biomicrite lenses next to porous "chalky" texture where leaching has occurred; other features:
--at 300-304: miliolid biosparite with miliolid biomicrite intraclasts
--at 307: brown, dense recrystallization limestone

307.5-309.5 Recrystallization limestone: extensive honeycomb solutioning with very high porosity and permeability; partial infill with large calcite crystals and drusy linings

309.5-317.5 Unsorted biosparite and sparse biomicrite; other features:
--at 309.5-312: packed biosparite with caprinids, oysters, miliolids, other forams; moldic porosity after some fossils
--at 312-313: packed biosparite without rudists
--at 313-317.5: mainly Toucasia biomicrite: some partly washed; solution-enlarged moldic porosity after caprinids, whole clams, rarely Toucasia; drusy coatings; little permeability

317.5-332.5 Recrystallization limestone: dense, fine to medium crystalline limestone to extensively honeycombed; yellow limonite-stained calcite infill; other features:
--at 318-324: no core
--at 325: beige chert nodule
--at 326-332.5: no core

332.5-337 Sparse miliolid-fossil fragment biomicrite: beige, allochems very fine, nonporous.

337-358.5 Dolomitic sparse fossil-fragment biomicrite to finely crystalline dolomite: burrowed, pinch and swell bedding; dolomite varies from slight to complete; fair to good porosity-- solution enlarged moldic after fossils with intercrystalline significant where dolomite content is higher; other features:
--at 337-337.5, 338.5-339: partial siliceous replacement
--at 337.5-338.5: highly porous honeycombed recrystallization limestone
--at 343-344: oysters & fossil fragments in slightly dolomitic marl
--at 347: dark gray chert

358.5-388 Sparse oyster-fossil fragment biomicrite: tan to beige, burrowed, marly streaks, some dolomite, upper few feet has good pinpoint porosity; other features:
--at 359-361: abundant gray chert
--at 362-364, 380-386: clayey streaks
--at 373-379: high-spired gastropod steinkerns with spar shell casts in partly washed biomicrite
--at 382-385: burrowed, some dolomite

388-404 Cavernous-recrystallized intervals within sparse oyster-Toucasia biomicrite: matrix lithology is same as above unit; excellent porosity-- solution enlarged moldic megapores after fossils to honeycomb to caverns; recrystallization of much matrix; some drusy infill; other features:
--at 388-393: USC of E reports 4-1/2' cavern
--at 392-397: oysters and Toucasia with vugs & honeycombing
--at 397-397.5: clayey streaks
--at 401-404: recrystallization limestone with extensive honeycomb solution

REGIONAL DENSE MEMBER

404-427 Clayey micrite and sparse fossil-fragment & whole-mollusc biomicrite: light gray to beige; burrowed; wispy clay streaks; gray carbonaceous streaks and pods; contains clam steinkerns including Pleuromya knowltoni, pectens, high-spired gastropods, oysters including Exogyra, miliolids and other forams; distinctive marker horizon.

KAINER FM.

GRAINSTONE MEMBER

427-467 Sorted fossil-fragment biosparite to unsorted fossiliferous intrasparite with biomicrite and recrystallization limestone: light tan; basic liths are biosparite and biomicrite but much micrite has been ripped up and redeposited as clasts; miliolids; generally good to excellent porosity-- intergranular, moldic after fossils, vugs, honeycomb, and caverns; other features:
--at 433-435: clayey streaks
--at 435-454: fossil fragment biosparite with intragranular, intergranular and moldic porosity up to 40%
--at 439,445: porous, finely crystalline dolomite
--at 447.5: medium gray chert nodules
--at 448-449: large oysters; burrows leached to megapore vugs
--at 454-456.5: light brown, dense micrite
--at 458-462: coarsely crystalline limestone with extensive honeycomb network
--at 464: caprinid, Monopleura
--at 466.5: high-spired snail steinkerns

467-484 Sorted miliolid biosparite to sparse miliolid biomicrite: white speckled, light to medium brown; miliolids, other forams, fossil fragments; squashed micrite intraclasts; slightly porous; other features:
--at 477-478: very sparse miliolid biomicrite wedge with apparent shrinkage cracks; micrite rip-up clasts in miliolid biosparite
--at 478-480: partly washed miliolid biomicrite with jagged fractures; some appear as solution enlarged vertical cracks up to 1" long & 1/8" wide; this is the lithographic micrite with incipient brecciation that Rose traces throughout the Edwards Plateau
--at 483: Toucasia

DOLOMITIC MEMBER

484-547 Cavernous recrystallization limestone developed in sparse miliolid-fossil fragment biomicrite: light gray to beige; highly cavernous; fine to very coarse recrystallized limestone with speleothems; terra rosa; other features:
--at 484-486: finely crystalline dolomite and medium to coarse recrystallized limestone
--at 486-490: siliceous recrystallized sparse biomicrite
--at 522-547: occasional beige chert nodules in recrystallization limestone fragments

547-566 Biomicrites (upper) to biosparites (lower) with interspersed recrystallized limestones: slight to cavernous porosity; other features:
--at 547-548, 550-552.5, 554-557: partly recrystallized, sparse miliolid-oyster fragment biomicrite
--at 548-550, 557.5-559, 562: cavernous, medium to coarse recrystallization limestone
--at 559-564: caprinid-oyster fragment biomicrite; some partly washed
--at 564-566: sorted miliolid-fossil fragment biosparite; much spar leached to give good intergranular porosity

566-596 Cavernous recrystallization limestone developed in fossil fragment-miliolid biomicrite and biosparite: other features:
--at 569-571: leached miliolid biosparite
--at 589-593: sparse fossil fragment biomicrite with dolomitic burrows

596-624.5 Unsorted oyster-fossil fragment biosparite to sparse miliolid biomicrite: beige to light brown; burrows with fair porosity; total porosity is slight; matrix gradational from micrite to partly washed to none; other features:
--at 598: abundant oysters in spar
--at 624.5: siliceous oyster fragments

624.5-629 Cavernous, fine recrystallization limestone: light brown; some extremely coarsely crystalline calcite infill

629-660 Sparse fossil fragment-miliolid biomicrite with clayey, dolomitic, spar-cemented, and recrystallized intervals: light gray to light brown; porosity varies from none to porous burrows to solution enlarged with some cavernous; other features:
--at 630,633,636: medium gray chert nodules; contain miliolids
--at 636-637: laminated micrite and sparse biomicrite
--at 639-640: clayey streaks
--at 639-647: burrow mottled; non-to slightly porous
--at 640.5-641: honeycombed, fine recrystallization limestone
--at 647-648: cavernous
--at 648-650: dolomitic
--at 650-652.5: current laminated miliolid biomicrite and intraclastic oyster biosparite
--at 652.5-654: recrystallized miliolid biomicrite; solution enlarged fractures
--at 656-658: stylolitic
--at 658-660: oysters
--at 660: solution-enlarged moldic porosity after a large caprinid just above a honeycombed recrystallization limestone; USC of E places the Edwards-Glen Rose contact here.

WALNUT FM.

660-677 Sparse mixed fossil biomicrite: light gray to orangish-beige; dolomitic to dolomitized; fair to good porosity in upper 9 feet-- intergranular with some solution-enlarged moldic after fossils and some vugs: burrowed; other features:
--at 660-666: heavily dolomitized burrowed miliolid biomicrite with very good microvugular porosity
--at 666-669: whole oysters and snails in dolomitized clam fragment biomicrite matrix; pronounced burrows; would weather to nodular marl
--at 669-671: many clay stringers; nonporous; weakly resistant
--at 671-677: some clayey wisps; dolomitic burrows; mottled; nonporous

677-711.5 Argillaceous oyster-fossil fragment biomicrite: medium gray to bluish gray; dolomitic beds and patches; carbonaceous; stylolitic; burrowed; some calcite-lined megapore vugs; other features:
--at 694-697: large whole oysters
--at 702-703, 705: abundant Exogyra valves and clam & high-spired snail steinkerns
--at 707: medium gray dense dolomite
--at 708-711.5: marly interval loaded with Exogyra texana

711.5 GLEN ROSE FM.

Punky, porous finely crystalline dolomite

RANDOLPH AFB CORE

U. S. Geological Survey cored a hole next to Randolph AFB on FM 1604 about 3.7 miles southeast of its intersection with I35. Location is just southwest across the street from Randolph High School.

Depth (feet)

604-621.5 GEORGETOWN FM.

Clayey sparse biomicrite: would weather to nodular limestone and marl; light bluish gray; abundant small pyrite crystals; upper 8 feet is heavily burrowed and fauna is mainly snaggletooth oysters in finely crunched biomicrite matrix; lower 9.5 feet has many clayey seams unbroken by burrowers and better whole faunal preservation--Kingena, Gryphaea, other oysters, clam and snail steinkerns, pectens, and ostracods; nonporous; other features:
--at 620.1-620.5: several small megapore vugs and small fractures with drusy calcite
--at 621.5: uppermost Edwards is a partly recrystallized Toucasia - miliolid limestone with an angular etched upper surface of 1/4 to 1/2 inch amplitude; pyritic Georgetown material fills in the relief

EDWARDS GROUP

PERSON FM.

621.5-634 Recrystallized miliolid grainstone: carbonaceous--large hunks to thin wispy laminae to dead oil accumulations; common Toucasia and fossil fragments; some former sparse biomicrite; some burrowing; fair porosity--intergranular and drusy lined megapore vugs; diagenetic mineralization undecipherable with hand lens; other features:
--at 624-625: clay stringers and carbonaceous stylolites
--at 628-629: hydrocarbon saturated Toucasia--miliolid grainstone

634-656.5 Toucasia - caprinid biolithite and talus grainstone: hydrocarbon stain common; carbonaceous hunks and styolites; large caprinids, dish-plate oysters, rudaceous snail & clam steinkerns, abundant fossil fragments; good porosity--moldic after caprinids and fossil fragments, some interparticle porosity; different diagenetic history than outcrop Edwards--very fine interparticle carbonate often present even after framework fossils leached, interparticle euhedral crystals, and some material as resistant as Toucasia shell is now coarsely crystalline calcite

656.5-682 Finely to medium crystalline dolomite: after sparse miliolid-fossil fragment biomicrite and thinly bedded intraclastic mixed fossil grainstones; wavy thin carbonaceous laminae & chunks and disseminated hydrocarbons; good porosity--intercrystalline and moldic after small fossil fragments; other features:
--at 657-657.5, 677-677.7: wavy stromatolitic interval--irregular erosion surfaces, breccia, and calcite filled fenestral porosity
--at 659.5: large megapore vug in fracture complex with extremely coarsely crystalline calcite crystals
--at 662.5-662.8: junky brecciated condensed zone with carbonaceous fragments
--at 662.8-664.4: beautiful collapse breccia--unsorted angular hunks of fine dolomite partly cemented by extremely coarsely crystalline calcite
--at 665-667.5: dolomitized miliolid-oyster fragment biosparite cut by scour surface with 2-1/2 inches relief; overlain by thinly bedded sparse biomicrite and grainstone with rudist debris
--at 667.5-672.5: some fossil molds and vugs filled with bluish calcite
--at 672.5-676, 678-679, 679.5-680: flint--highly irregular borders
--at 672.5-677: relict flaser-like bedding with some small burrows
--at 681-682: dolomitized intraclastic fossil fragment grainstone; vuggy; calcite snail steinkerns; few burrows

682-691 Toucasia - caprinid biolithite and intraclastic fossil fragment grainstone: biolithite with recrystallized fossil fragment biomicrite matrix; grainstone has Toucasia, caprinids, clams, oysters, miliolids and fossil fragments; dolomitic in part; hydrocarbon stained; interframework calcite crystals; fair porosity--moldic after fossils megapore vugs, shelter, and small near vertical fractures; other features:
--at 682-685: some small flint nodules

691-702 Finely to medium crystalline dolomite: light brown due to disseminated hydrocarbons; carbonaceous bits, pieces and laminae; good porosity--intercrystalline, moldic after fossils and vugs; other features:
--at 691.4-695: dolomite after whole mollusc packstone; large megapore vugs and a 1-1/2 inch horizontal separation with extremely coarse calcite crystals
--at 695-695.6, 696-698: oyster, Toucasia and other fragments in relict burrowed biomicrite and grainstone
--at 698-702: flint with highly irregular boundaries

702-709.5 Toucasia biolithite and miliolid-fossil fragment grainstone: interparticle material is very fine grunge; many fossil fragments are dissolved and gone; poor to fair porosity--some large megapore vugs with very coarse calcite crystals

709.5-721.5 Medium crystalline dolomite: light to medium brown due to hydrocarbon staining; punky; several flint horizons--relict texture is dolomite with Toucasia and oyster fragments; lower part cut by many calcite veinlets; other features:
--at 710: very large oysters
--at 713.5-716: moldic porosity after clams & snails; vugular
--at 718-720.5: caprinid biolithite

721.5-730.2 Recrystallized miliolid-fossil fragment grainstone & wackestone: dense carbonate encrustation on grains--then grains sometimes removed; fair porosity--moldic near top; carbonaceous stylolites; other features:
--at 721.5-723: caprinid-dishplate oyster biolithite
--at 723-726: grainstone--caprinids, mollusc steinkerns, oysters, miliolids, fossil fragments
--at 729.5: dolomite interbed

730.2-751.5 Medium crystalline dolomite: light to dark brown from varying oil saturations; wispy carbonaceous stringers; good intercrystalline porosity; small calcite healed fractures; other features:
--at 730.2-733: heavily oil stained
--at 730.5, 733.5-734.5: junked up breccia zones
--at 733.6, 736.4, 746: flint nodules
--at 736-736.3: wavy stromatolites with intercalated thin breccias
--at 737-738: random pattern of bluish calcite healed fractures
--at 740.6-740.9: oyster and carbonaceous rich
--at 742-744: resistant light gray dense dolomite patches
--at 748-750: bluish-white calcite filling fossil molds and vugs

751.5-755.5 Toucasia biolithite overlain by recrystallized, dolomitic, burrowed fossil fragment grainstone-wackestone: oysters, miliolids; carbonaceous stylolites; dense

755.5-762 Medium crystalline dolomite: light to medium brown; wispy carbonaceous laminae; punky; good porosity--intercrystalline and moldic after fossil fragments; other features:
--at 755.5-756.5: Toucasia biolithite

762-780.5 Recrystallized dolomitic fossiliferous grainstone-wackestone: interframework material is usually dense, inscrutable (to the hand lens), very fine diagenetic carbonate; miliolids, oyster and other fragments; much looks lensy and subtidal; poor porosity; other features:
--at 763.5-764.5: microfaults and breccia
--at 774.5: Toucasia, clams, carbonaceous hunks
--at 774.5-780.5: large megapore vugs with calcite crystals; interframework crystals also

780.5-789: Caprinid biolithite to rudist grainstone-wackestone: dolomitized in part; some dense very fine interframework gunk; calcite crystals growing randomly through rock; carbonaceous stringers; Toucasia; other features:
--at 784, 785: flint including caprinid mold

789-805 Recrystallized fossil fragment grainstone-wackestone and dolomite: hydrocarbon stain and thin carbonaceous stringers; miliolids, Toucasia, oyster and other fragments; calcite crystals growing randomly; variable porosity; other features:
--at 790.8, 791.5, 804.5: flint
--at 791: dense fractured layer
--at 794, 797.5, 798.2: quartz crystal clusters growing into megapore vugs
--at 800.8-805: dense, nonporous

805-810 Medium crystalline dolomite: light to medium brown; oil stained; good porosity--intercrystalline and moldic after fossil fragments; small calcite healed fractures; other features:
--at 805-806.5: heavy oil staining--earthy looking; carbonaceous fragments and stringers
--at 807.3-810: bluish calcite fills some large megapore vugs, oyster and fossil fragment molds

810-830.5 REGIONAL DENSE MEMBER

Clayey sparse biomicrite: dense; nonpermeable; little carbonaceous fragments with pyrite drusy; purer carbonate intervals are slightly dolomitic; flaser bedding aspect; whole clams & snails with fragments; other features:
--at 811.2-812, 817-817.2, 820: very clayey
--at 818-818.3: partly washed miliolid-snail biomicrite
--at 822-830: homogeneously lensed--gray & white mottles on light brown background; wispy clay stringers unbroken by burrowers

KAINER FM.

830.5-871 Miliolid-fossil fragment grainstone: on the outcrop these rocks are textbook biosparites--the core has identical allochems but instead of sparry calcite cement there is a dense very finely crystalline carbonate that resists acidizing better than the fossils; some faceted calcite and dolomite crystals have grown in intergranular porosity; miliolids, oysters, highspired snails, caprinids, and fossil fragments; finely crystalline intraclasts; wispy carbonaceous laminae, chunks, and stylolites; usually light brown from disseminated hydrocarbons; fair porosity--intergranular, some moldic after fossils, and some large megapore vugs with extremely coarse calcite crystals; other features:
--at 830.5: caprinid
--at 847.5-848: blue-green algal trapping of small grains
--at 850.5-871: some intercalated thin beds and lenses of miliolid wackestone and packstone with a few burrows
--at 862.5: flint

871-879.5 Dolomitized grainstone-wackestone: dolomitized thin-bedded miliolid grainstones and sparse miliolid-oyster & other fragment biomicrite; some burrowing in wackestones; carbonaceous laminae; calcite healed fractures; fair porosity--intercrystalline and vugular; other features:
--at 871-874: ramifying calcite veins
--at 874: odd mosaic of megapore vugs
--at 874-876: flint nodules

879.5-897 Miliolid grainstone: prolific miliolids with fossil fragments; micrite intraclasts; fair porosity--intergranular with pretty calcite crystals growing in voids; other features:
--at 879.5-891: sorted miliolid-fossil fragment grainstone
--at 891-894.2: unsorted grainstone--miliolids, large snail & clam steinkerns; cement is clear mucilaginous-looking glaze of calcite
--at 894.2-897: unsorted intraclastic miliolid grainstone with dense, gray, very sparse biomicrite layers

897-918 Finely to medium crystalline dolomite: light to medium brown; fair to good intercrystalline porosity; other features:
--at 897-98: many carbonaceous laminae; recrystallized oysters, Toucasia
--at 899, 900, 902: flint
--at 899-903: ramifying bluish calcite veinlets, vug fillings, and random crystals
--at 901-901.5: caprinids and whole clams
--at 903-904, 908.8-909.3, 917.5-918: nonporous, dolomitized miliolid grainstone
--at 904-904.5: dolomitized blue-green algal head with breccia
--at 904.5-908: poor recovery
--at 908-917.5: dolomite after thinly bedded, unburrowed sparse biomicrite with some relict packstone-grainstone

918-934 Dolomitized miliolid-fossil fragment grainstone: miliolids, some snails, clams, oyster & other fragments; parts are thinly bedded and burrows are scarce; carbonaceous laminae; nonporous to poor-fair porosity--intercrystalline, vugular, and some short gashy fractures; other features:
--at 918-920: large megapore vugs elongate parallel to bedding--enlarged after clams?; some brecciation
--at 920-920.7, 927-929, 931.5-933: dense dolomite after sparse fossil fragment biomicrite
--at 924-925: dense and nonporous
--at 933.5: snail-rich coquina

934-966.5 Finely to medium crystalline dolomite and dolomitized wackestone-grainstone: mostly tidal flat deposits--thinly bedded with few burrows, stromatolites, and breccias; carbonaceous laminae; nonporous to fair-good porosity--intercrystalline, vuggy, moldic after fossil fragments, and partly healed small fractures; vugs with partial calcite crystal infill; other features:
--at 934.2, 951.5-952, 958-958.5, 960-964: breccia
--at 936.5, 948.4, 955-955.6, 958-958.5, 962: flint nodules; some with gashy vertical fractures
--at 936.5-937, 940.2-941.2: oyster-rich layers
--at 937-938: dolomite after sparse rudaceous whole mollusc biomicrite
--at 946.3: dense finely crystalline dolomite with near vertical gashy shrinkage fractures
--at 957-957.5, 960-962.2: stromatolitic
--at 958-958.5: disastrous breccia texture and oddly shaped chert
--at 958.5-960: dense, nonporous, dolomitized thinly bedded small fossil fragment grainstone
--at 960-962.2: pretty, semi-stratified dolomite breccia
--at 962.2-964, 966-966.5: ugly brecciated dolomite with ramifying bluish calcite areas

966.5-971.5 Cherty unsorted fossiliderous grainstone: other features:
--at 966.5-968: unsorted coquina--large clams & snails with small fragments; fossils dissolved away leaving moldic porosity in dense very fine carbonate interframework
--at 968-971.5: dense dolomitized grainstone--many tiny fossil fragments with some large oysters; few burrows; carbonaceous laminae in bunches

971.5-976.5 Medium to finely crystalline dolomite: beige; largely after sparse fossil fragment biomicrite; thin to thick wavy laminae; few relict intraclasts; good porosity--intercrystalline and moldic after small fossil fragments; other features:
--at 971.8: burrow mottling
--at 972.6, 972.8, 974.2, 974.8, 975.7: thin carbonaceous laminae; sometimes oyster rich
--at 973-975: near vertical fractures; slightly enlarged
--at 973.6: silicified interval- 0 to 2 inches thick

976.5-978 No core

978-982.5 Dolomitic miliolid-oyster grainstone: several few inch thick oyster placers; poor to fair interparticle porosity; other features:
--at 978.1: carbonaceous interval
--at 979.1: flint layer - 1 inch thick

982.5-986 Finely to medium crystalline dolomite: beige; thin to thick irregular laminae--no burrowing; relict intraclasts; good porosity--intercrystalline, moldic after small fossil fragments and small snails & clams, vertical fracture with calcite crystals; other features:
--at 982.5-982.9: thin wavy carbonaceous laminae
--at 985.5-985.7: intraclastic oyster placer with calcite infilled fenestral porosity

986-990.5 Dolomitized miliolid-oyster grainstone: some was originally wackestone and packstone; several 1 to 3 inch oyster-rich shell layers resting on scoured miliolid-fossil fragment biomicrite; other features:
--at 987.5: very carbonaceous interval

990.5-996 Finely to medium crystalline dolomite: light tannish gray; some intraclastic layers; some burrowing; fossil fragments crunched smaller than usual; irregular cross-cutting depositional lenses; some thin unburrowed laminae; fair to good porosity--mostly intercrystalline, some moldic after small fossil fragments; other features:
--at 991.8-992, 993.9-994, 994.7-994.9: carbonaceous laminae
--at 993-994.5: dolomitized small fossil fragment grainstone with many oysters
--at 995-995.5: three shades of gray show burrowed fossil fragment wackestone brecciated by dessication

996-1002 Coquina: bioclastic grainstone with pieces of caprinids, oysters, clams, snails, echinoids, miliolids, _Toucasia_, bryozoa, etc.; dolomitic; some burrowing; good interparticle porosity; other features:
--at 1000.5-1001: caprinid biolithite with _Toucasia_

1002-1008.7 Medium crystalline dolomite: irregular thin layers unbroken by burrowers; good porosity--intercrystalline with some moldic after fossil fragments and mostly healed thin fractures; other features:
--at 1002.2, 1002.9, 1004.5-4.9: carbonaceous laminae
--at 1002.4, 1008.7: flint lenses up to 1/2 inch thick
--at 1002.9-4.0: dolomicrite intraclasts and snail steinkerns dominating shell placer lenses
--at 1004-5: stromatolite interval evidenced by very thin crinkly laminae around blotched texture
--at 1005.0-5.8: boxwork and breccia with large megapore vugs--evaporite supratidal deposit

1008.7-1013 Very finely intercalated carbonaceous and finely crystalline dolomite laminae: poor porosity; other features:
--at 1012-1013: some burrow mottling

1013-1028 Medium crystalline dolomite: beige & gray; alternates from burrowed to finely laminated (sometimes carbonaceous) to shell fragment placers; good porosity--intercrystalline and moldic after small fossil fragments; other features:
--at 1013-1018, 1019-1020: many burrows with abundant small fossil fragments and some small clams
--at 1018-1019, 1025-1028: fine laminae undisturbed by burrowers
--at 1020, 1022.0-22.5, 1024.5-25.0, 1027.5-28.0: numerous thin carbonaceous laminae
--at 1020.0-21.5, 1022.5-23.0: odd mottling; possible cyanophyta horizons
--at 1021.5-22.0, 1023.2-25.5: dolomitic miliolid-oyster-fossil fragment coquina lenses

1028-1038.5 Dolomitic sparse fossil fragment biomicrite: some recrystallization; burrow mottled--fossil fragments even finer than usual; subtidal; poor porosity; other features:
--at 1028-28.5, 1031.2-31.5, 1037.0-37.8: many thin carbonaceous laminae; stylolites

1038.5-1040 Medium to finely crystalline dolomite: finely xline gray dolomite cut by large burrows filled by medium xline beige dolomite with moldic porosity after fossil fragments; good porosity

1040-1045 Dolomitized coquina: layers of abundant high-spired snail steinkerns, oysters and other fossil fragments; some placers are burrowed; good interparticle porosity

1045-1047.8 Finely crystalline dolomite: brownish gray; numerous small bluish flint nodules--relict texture shows dolomitized fossil fragment grainstone; good intercrystalline porosity

1047.8-1059 Dolomitized fossil fragment coquina: mostly grainstone but some was probably packstone or wackestone; dolomicrite intraclasts; coquina includes _Toucasia_, clams, snails, oysters, bryozoa, echinoids, miliolids, and other debris; mostly in irregular layers around 1 inch thick; good interparticle porosity with some moldic and intercrystal-

line; other features:
--at 1048.2: flint lense
--at 1049.5-50.0: Monopleura bunches
--at 1050.5, 52.2, 52.8: carbonaceous stylolites
--at 1050.5-51.5, 1055.5-56.0, 1057.0-57.2: Toucasia boundstone with Monopleura
--at 1053-54: incipient vertical fractures

1059-1073.5 Medium to finely crystalline dolomite: variegated lensoidal bedding and thin wavy laminae in former packstone-wackestone sequence without large burrows--cf. flaser bedding; some were shell fragment grainstone lenses; good intercrystalline porosity; other features:
--at 1060-62.5, 1065.0-65.5, 1066, 1067-68, 1069-70: bluish chert with relict fossil fragments
--at 1072.7-73.2: stromatolite--intraclastic mess
--at 1071-73.5: some thin wavy carbonaceous laminae

1073.5-1074.5 Finely crystalline dolomite: very finely laminated with numerous carbonaceous stringers; no burrowers; several near vertical fractures but without solution enlargement

1074.5-1096.5 Dolomitized fossil fragment grainstone with wackestone and packstone: diverse fossil debris including rudistids; thinly bedded dolomicrite to intraclastic coquina; some burrowing--often characteristic medium brown in light beige or gray; good porosity--mainly intercrystalline with moldic and interparticle; very thin carbonaceous laminae; small near vertical fractures with slight enlargement; other features:
--at 1076-77: flint nodules in gray finely crystalline dolomite
--at 1077-79, 1081.5-86: typical Comanche Peak-like lith--medium brown dolomitized burrows in light brown dolomitic fossil fragment matrix; dolomicrite intraclasts at angles to bedding; few vugs; caprinid debris
--at 1079-80: thinly bedded fine dolomite to snail coquina layers; no burrowers; high intertidal
--at 1080-81.5, 1087.5-96.5: fossil fragment coquina--some snail-rich with larger fragments but most with very small fossil fragments

1096.5-1122 Medium crystalline dolomite: poor recovery interval; other features:
--at 1096.5-1103: about 2 feet rock fragments recovered--brown dolomite with grayish mottles; good intercrystalline and moldic porosity after unsorted fossil fragments
--at 1103-1112: about 5 feet recovered core--probably dolomitized fossil fragment wackestone; some gashy near vertical fractures; some carbonaceous laminae
--at 1112-1122: about 5 feet recovered--upper 2 feet as above; middle foot a dolomitized small fossil fragment packstone; bottom 2 feet with resistant gray mottles in usual brown dolomite; some wavy carbonaceous laminae

1122-1142 Dolomitized burrowed biomicrite and rudist biolithite: some large oysters--Exogyra texana?, clams, snails, rudists and fossil fragments; nonporous to poor porosity--small and large megapore vugs with calcite crystals and numerous unenlarged small fractures; other features:
--at 1122-1125: dolomitized, carbonaceous and clayey seamed, sparse oyster biomicrite
--at 1125-1131: mottled texture--resistant gray dolomitized blotches with softer brown dolomite burrows
--at 1131-1134: dolomitized caprinid biolithite with Toucasia in same mottled texture as above
--at 1136: Toucasia in same resistant gray and weak brown mottled texture
--at 1138-1140: Toucasia with large snails and oysters; probable biolithite around 1139
--at 1140-1142: dolomitized, burrowed, sparse oyster biomicrite; contact with Walnut very gradational and arbitrary

1142-1183.7 WALNUT FM.
Dolomitic sparse Exogyra texana-BRB biomicrite: BRB's (black rotund bodies of Ted Small, U.S.G.S., San Antonio) are presumably little fossil fragments colored by impregnation with reduced, black, finely divided iron; burrow mottled to flaser bedded; bunches of thin clayey and carbonaceous seams are common; more resistant (purer?) limestone layers are dolomitic to dolomitized; stylolitic; some mottled texture as above--gray resistant sparse BRB biomicrite cut by weak brown dolomite burrows; poor porosity--some very large megapore vugs, slightly solution enlarged vugs after snails, enlargement of small fractures; other features:
--at 1152-55: dolomitic BRB & other fossil fragment grainstone with burrows
--at 1159.5-60.2: burrowed miliolid-fossil fragment grainstone
--at 1161: dense, gray, finely crystalline dolomite interbed
--at 1162-62.7: punky fine dolomite; brecciated and vuggy in part
--at 1181.7-82.4: abundant large snails and miliolids

GLEN ROSE FM.

1183.7-1192 (bottom of hole) Finely to medium crystalline dolomite: orangish-brown to medium brown; dolomite after intraclastic miliolid grainstone, sparse miliolid-fossil fragment biomicrite and sparse whole mollusc biomicrite; some calcite healed fractures; good porosity--intercrystalline, moldic after fossils, fracture, and small-large megapore vugs with extremely coarsely crystalline calcite lining

NEW BRAUNFELS CORE

Texas Water Development Board Core DX-2 was drilled northwest of New Braunfels along FM 1863 about 1.6 miles west of its intersection with Highway 46. The hole started at 937 feet elevation and the interval cored was 275 to 432 feet below surface. The way the core is numbered and boxed it seems possible that some pieces are out of sequence. Core is now stored in the Well Sample Library, Room 18b, Balcones Research Center, Univ. Texas at Austin.

Depth (feet)

EDWARDS GROUP

275-298 Fine-medium recrystallization limestone: primarily after sparse fossil fragment biomicrite; beige; dense; slight to good porosity--intercrystalline, meso- to megapore channels, solution-enlarged fractures; other features:
--at 275-276, 282, 286, 293-297: channel porosity with some coarsely crystalline calcite infill and terra rosa
--at 277-278, 283, 289, 293: bioclastic grainstone to fossil fragment coquina--oysters, snails, clams, miliolids
--at 278-280, 290, 297-298: medium crystalline granular calcite framework with good intercrystalline porosity
--at 287.5: chert; liesegang banded

298-309 Caprinid biolithite: matrix varies from medium recrystallization limestone to unsorted mixed-fossil grainstone; fauna includes dish-plate oysters, Toucasia, snail steinkerns, caprinids, clams, forams, echinoid and other debris; brittle; tannish-gray; moldic porosity after caprinids and mollusc fragments

309-313 Unsorted to sorted intraclastic biosparite: snail steinkerns, oyster & clam fragments, Toucasia, miliolids & fossil debris; moldic porosity after fossils; some megapore vugs

313-330 Recrystallized sparse to packed biomicrite: parts were grainstone; dense; beige; oysters, miliolids & fossil fragments; non- to slightly porous--some moldic after fossil fragments, few small mesopore vugs; other features:
--at 316-328: poor recovery--solution zone suggested by iron-stained, more heavily recrystallized rock fragments
--at 329.5: unsorted fossil fragment coquina

330-348.5 Coquina: mixed fossil grainstone of oysters, pectens, clams, snails, miliolids, abundant fossil fragments; fair to good moldic & interparticle porosity; other features:
--at 332: chert
--at 336: thin, dish-plate sized oysters

348.5-371 Sparse biomicrite: dense; beige; burrowed; miliolids, oyster and other fossil fragments; nonporous to cavernous; other features:
--at 348.5-353, 354-362: poor recovery suggests caverns
--at 349, 365.5, 367.5, 368.5: finely crystalline dolomite
--at 363, 365.5, 368.5-370: megapore channels and vugs; some with terra rosa and calcite drusy
--at 367: miliolid intrasparite with chert

371-375 Coquina: fossil fragments--oysters, clams, caprinid tubes, Toucasia, echinoids, and others; miliolids, dasyclads; fair to good interparticle and moldic porosity

375-390 Recrystallized fossiliferous wackestone-packstone-grainstone: varying amounts of fossil debris--some crumbly coquina but mostly burrowed sparse biomicrite; fair to excellent porosity--solution enlarged fractures; channels; intergranular in burrows and coquina; other features:
--at 375, 379.5-380, 386-388: megapore channels with terra rosa
--at 388-390: dolomitic, recrystallized limestone

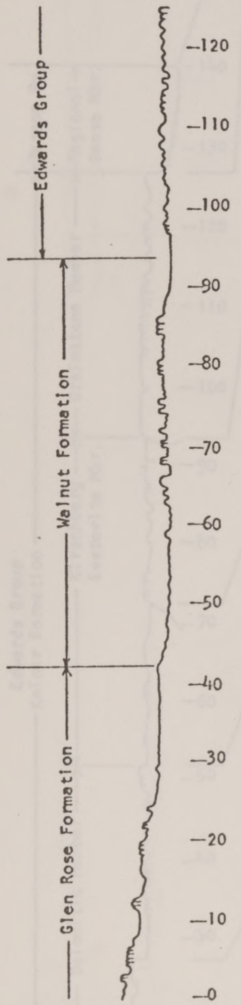
390-402 Fossiliferous grainstone with dolomite and biomicrite interbeds: miliolids, dasyclads, snails, oysters, clams, echinoid and other debris; burrows; intraclastic; fair to excellent porosity--interparticle, moldic after fossils and burrows, intercrystalline, channel, bedding surface and near vertical fractures, small megapore vugs; other features:
--at 391: dolomitized burrows
--at 392.5-394, 396-397: finely crystalline dolomite after fossil fragment grainstone; small megapore vugs standing roughly vertical and shaped like gypsum crystals
--at 396, 401: channels developed in burrows

402-410 Cavernous zone suggested by poor recovery and rounded rock fragments: other features:
--at 402, 408: recrystallized burrowed fossil fragment grainstone
--at 405, 407, 409: finely crystalline dolomite with relict small fossil fragments

410-432 Finely crystalline dolomite to dolomitic clayey burrowed biomicrite: light to medium gray; slightly to very clayey--emphasized by wavy laminae and flaser bedding; quite carbonaceous; mottled and punky--would form marly-nodular recessive slopes; oyster and other fragments; slight to good porosity--intercrystalline, moldic after fossil fragments and clams, small fractures, and some large mesopore vugs; other features:
--at 414-417: dolomitized caprinid biolithite with Toucasia

BULVERDE PEAK SECTION

Located on the old E. D. Uegker ranch off Smithson Valley Road
In the northeast section of Bulverde quadrangle, Bexar Co.
Section measured along dirt road heading west than north to top
of Bulverde Peak.



Miliolid-fossil hash intrasparite to sparse miliolid-fossil fragment biomicrite: miliolids, other forams, snail steinkerns, fragments of oysters, clams & rudists; micritic intraclasts; burrowed, dolomitic; stylolitic; chalky appearing due to weathering-- dedolomitization evidenced by calcite rhombohedrons and relict rhombs within spar; slight to fair porosity-intergranular; other features:
--at 103.5: mudcracked grainstone-- barely moved intraclasts of dolomitic, very sparse miliolid micrite several inches across-- incipient breccia

Marl: weak, recessive, mostly covered

Exogyra texana marl and sandy intraclastic biosparite: nodular to somewhat flaggy, clayey, sparse *E. texana* biomicrite with interbedded biosparites as in subjacent unit but with 0 to 10% fine quartz sand; iron-stained; nonporous; other features:
--at 81,86: corrosion surface-- bored; heavily iron encrusted; attached *E. texana* valves

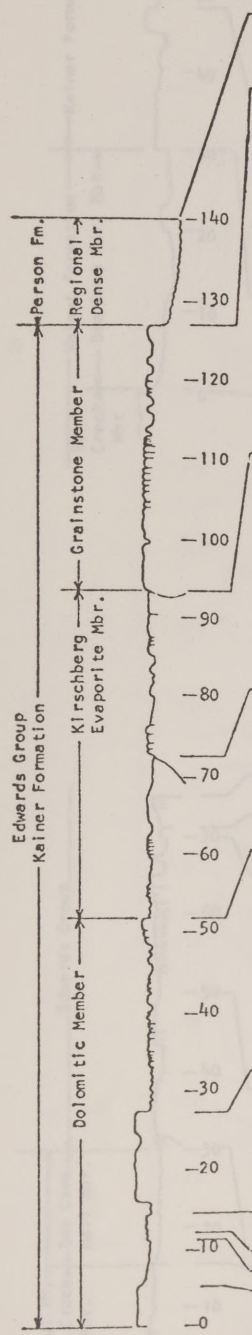
Intraclastic biosparite: ranges from unsorted, rudaceous micrite intraclastic, snail steinkern-miliolid-oyster fragment biosparite to sorted miliolid biosparite to sorted, bimodal, intraclastic biosparite with 1 mode of abundant whole *Exogyra texana*, *Nerinea*, clam fragments and another mode of fine to medium micrite intraclasts & forams; iron-stained, nonporous

Finely to coarsely crystalline pseudosparite: iron-stained, poor exposures on flattish slope

Finely to medium crystalline dolomite and dolomitic biomicrite: orangish-stained beige to light gray; characteristic lithology is punky dolomite with moldic porosity after sparse fossils; interbeds of burrowed, dolomitic, slightly recrystallized, miliolid-mollusc biomicrite to intraclastic biosparite; some marly intervals; other features:
--at 30-42: very steep slope; calichified and covered except for some thin pseudosparites and travertine; former evaporite horizon?
--at 6: corrosion surface-- bored, iron-stained, cemented *Exogyra texana* valves that are themselves bored
--at 2-3, 4-6: laminated to thinly bedded, miliolid-*Nerinea* biomicrite & intraclastic biosparite

COLORADO RIVER BLUFF SECTION

Section measured on Colorado River cutbank near the main fault-line scarp of the Balcones fault zone below Tom Miller dam in Austin, Travis Co. Begin at water level on west bank of river and work upward and northward around cliff to Redbud Trail. Continue measuring upward and southward along Redbud Trail.



Marl and nodular to flaggy sparse biomicrite: soft; clayey; burrowed; clam steinkerns include *Pleuromya knowltoni*, echinoids, oysters include *Exogyra texana*; nonporous; distinctive unit known as Dr. Burt beds or regional dense marker

Unsorted intraclastic biosparite & poorly washed biosparite, rudist biolithite, & marl: nonporous to fair moldic porosity after fossils; other features:
- --at 93.5-99.5: lenses of inclined & thinly bedded cherty micrite & sparse miliolid biomicrite grading upwards to intraclastic, rudaceous oyster biosparite; grades laterally to reefoid talus-- cherty, dolomitic, burrowed, partly washed, huge oyster intramicrudite
- --at 99.5-100: oyster marl-- clayey, nodular, burrowed, fossil fragment-snail oyster biomicrite
- --at 100-104: *Toucasia*-"dish-like" oyster biolithite; partly washed, fossil fragment biomicrite matrix; cherty at top
- --at 104-104.5, 108-108.5, 112.5-113.5: blue-green algae
- --at 104.5-107: thin-bedded, unsorted clam-snail-miliolid-oyster fragment biosparite
- --at 107-107.5, 114-116.5, 117.5-119, 121.5-123: marl-- burrowed, clayey sparse biomicrite
- --at 108-108.5: burrowed, poorly washed, miliolid intrasparite-- storm jumbled bed
- --at 108.5-109, 110.5-112.5: unsorted intraclastic gastropod biosparrudite; gravity settled micrite, pellets & miliolids in high-spired snail coquina; coarsely crystalline geopetal spar
- --at 123-127: *Toucasia* biolithite & debris with snail, serpulid, miliolid, fossil hash biomicrite matrix

Evaporite-solution collapse interval-- recrystallization limestone, dedolomite, chert, & intraclastic biosparite; other features:
- --at 68.5-72.5: highly porous wedge of cavern fill & rexln ls; fenestral to channel meso- & megapores; terra rosa
- --at 73.5, 74: chert; relict texture of dolomitized oyster fragment-sponge spicule biomicrite
- --at 73.5-82: packed intraclastic, pelletal, miliolid-oyster & other fossil fragment-snail microsparite; incipient stylolites to strong solution-condensation; badly weathered with coarse calcite infill in places
- --at 82-93.5: dedolomite-- zoned rhombs in inclusion-filled poikilotopic calcite; highly porous-- meso- to megapore channels with drusy to extremely coarsely crystalline calcite infill
- --at 86-87: aesthetic chert-- texture as surrounding lithology

Medium crystalline dolomite: light gray to beige; punky to pulverulitic; good porosity-- intercrystalline to moldic after fossils; cherty; dedolomitization; original lithology mainly burrowed sparse miliolid-whole clam & snail-fossil fragment biomicrite; other features:
- --at 55.5-57.5: highly porous dolomite after laminated microcoquina
- --at 64-67.5: breccia clasts of dense dolomite in porous dolomite
- --at 67.5: 2 ft. long brown & blue-gray chert nodules; silicified breccia-- clasts of dolomitic packed miliolid-fossil fragment biomicrite
- --at 68.5-72.5: pulverulite wedge-- 0 to 4 ft. thick

Finely to medium crystalline dolomite: light to medium gray; punky; moderate to complete dolomitization of sub- to supratidal lithologic sequences - i.e. sparse high-spired gastropod, whole clam, dasycladacean algae biomicrite to algal stromatolites; dessication crack & intraclasts, scabby crusts; dedolomitization; good porosity-- intercrystalline to moldic after fossils; other features:
- --at 30-30.5, 33.5-34: slightly siliceous recrystallization limestone with meso-megapore channels
- --at 30.5-32: stromatolitic to bedded finely crystalline dolomite with patches of very coarsely crystalline poikilotopic spar containing vestigial dolomite rhombs
- --at 32-33.5, 34-35.5: medium gray dolomite burrows in light gray dolomitized groundmass
- --at 37, 39: gray chert
- --at 43-44.5: rudists, wormtubes, high spired gastropods; dolomitized lumachelle

Cherty, finely to medium crystalline dolomite: light gray; good porosity-- intercrystalline and moldic after fossil fragments; chert in nodules and as microquartz-chalcedony void fillings; dedolomitization evidenced by relict zoned dolomite rhombs in inclusion filled poikilotopic calcite; patches of very coarsely crystalline secondary calcite crystals; other features:
- --at 17,25: stromatolites overlain by dolomitized burrowed sparse fossil fragment biomicrite
- --at 26: silicified finely crystalline dolomite; cross laminations-- planar-tabular with some micro-festoons

Dolomitic sparse gastropod biomicrite: darker dolomitized burrows; good porosity-- pinpoint and moldic after whole clams & high-spired snails

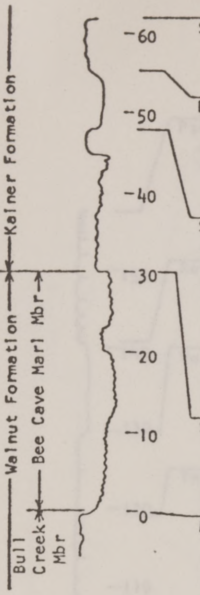
Finely crystalline dolomite: thinly laminated, undulose bedding (stromatolitic); good porosity

Covered slope - no outcrop

Finely crystalline dolomite: light to medium gray; good porosity-- intercrystalline to solution-enlarged moldic after fossil fragments

WEST LOOP FREEWAY SECTION

Measured in roadcut being quarried immediately north of West Loop Freeway-Bee Cave Road Intersection, southwestern part of Austin West quad, Travis Co., Texas.



Sorted very fine calcarenite: light tan, fair porosity, medium to thick bedding with planar beds and tabular-planar cross-beds; allochems are fossils (echinoid debris, miliolids, other forams, oyster frags) and very fine intraclasts with pellets & oolites in medium to coarsely crystalline poikilotopic calcite cement; thin lenses & layers of chert

Dolomite & solution-collapse breccia: basal 6" to 7' is very finely (with some finely) crystalline dolomite with minor micrite (dedolomite?) as pervasive network, 1% quartz sand & silt, some small megapore channels. Above a very irregular contact lies a cherty, recrystallized solution-collapse breccia with highly angular rudaceous clasts of fine dolomite (some uniformly crystalline, others with coarse spar & intraclast ghosts) encrusted by medium to coarsely crystalline bladed to equant spar; cementation-reduced megapores in collapse breccia; 25% porosity

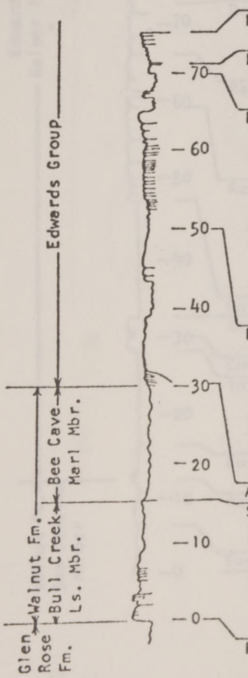
Sparse foram and fossil fragment biomicrite: beige, burrowed with resistant nodules between, with Dictyoconus, miliolids, clam and juvenile snail steinkerns, oysters, echinoid spines, green algae, bryozoa, and abundant fossil fragments; other features:
--at 47-48: irregular dolomitization front pervasively replaced by silica (up to 70%) giving distinct upper surface showing solution relief; allochem ghosts similar to liths below
--at 46-47: burrowing decreases upward; scattered dolomite rhombs in finely crystalline pseudospar (dedolomite?)
--at 37-41: resistant micritic nodules surrounded by orangish-red filled burrows
--at 30-37: medium-to thick-bedding divided by clay-rich seams
--at 30: abrupt conformable contact apparently due to greater $CaCO_3$ percentage in Edwards Fm.

Sparse argillaceous mixed-fossil biomicrite (marl): light gray fresh, weathers tan, weakly resistant, nodular, burrowed, with Dictyoconus, miliolids, whole snails, pelecypod fragments, echinoid debris, other fragmented fossils, and numerous whole bored valves of Exogyra texana; percentage distribution of various fossils fluctuates throughout; other features:
--at 20-23: greater resistance due to less clay

Member is 24 feet thick. Upper bed is resistant with iron-stained top; with Exogyra texana and rudaceous gastropods.

BLANCO - COLORADO RIVER DIVIDE SECTION

Measured in drainage ditch and roadcut on Ranch Road 165, southeastern corner of Yeager Creek quad, Blanco Co., Texas.



Nodular, burrowed, Toucasia-miliolid-oyster fragment intraclastic biosparite with some intergranular porosity

Porous solution zone: dolomitic sparse biomicrite eaten into large megapore-cavernous porosity with remnant horizontality and room & pillar structure; later sparry calcite infilling has reduced porosity to 15%

Dolomitized stromatolites & intraclastic fossil fragment flags: 1/16" to 2' bedded inter- to supratidal sequence; very finely to finely crystalline dolomite from few to 85%; inwashed allochems in flags include Nerinea, few caprinids, oyster frags, miliolids, & dolomicrite intraclasts; solution-enlarged moldic porosity after fossil frags up to 12%
--at 65-1/2-66-1/2, 67-1/2-70, 71-1/2: pulverulitic dolomite
--at 57-59, 61-64-1/2: punky dolomite with solution-enlarged moldic porosity after fossils and gypsum crystals
--at 56-56-1/2: lumachelle of in washed Nerinea steinkerns in stratal dolomite
--at 55-1/2-56: dolomitic oyster fragment intrasparite; clasts of stratal dolomite
--at 53-54; 57-61; 63-1/2-65: blue-green algal stromatolites
--at 50-53: nodular sparse biomicrite; subtidal

Dolomitized burrowed rudistid talus and biolithites: distinctive large grayish-brown dolomitized burrows in whitish-tan calcitic rock; framework-building organisms begin with caprinids, then caprinids & Toucasia, then oysters, followed by Monopleura; good intercrystalline (dol.) porosity and moldic after fossil fragments; dolomite from 0-85%
--at 43-44: unsorted intraclastic oyster biosparite
--at 36: Nerinea placer
--at 30-1/2-33: laminated sorted fossiliferous oosparite; fossils parallel bedding, few porous burrows

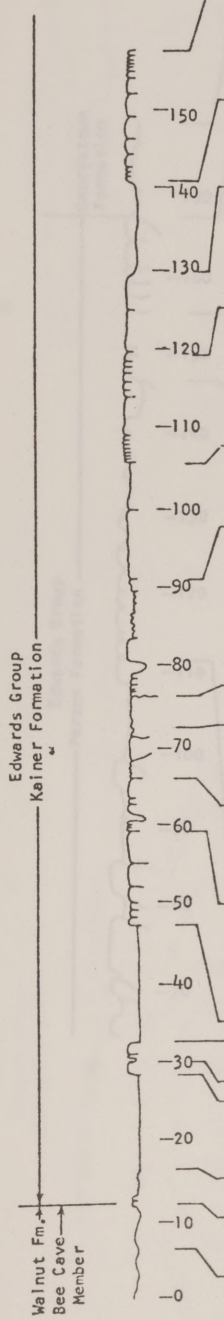
Argillaceous sparse Exogyra texana - mixed fossil biomicrite (marl)

Silty poorly-washed biopelsparite to sparse biomicrite: quartz silt (0-50%); miliolids, other forams, Exogyra, Trigonia, clams, high-spired snails, echinoids, bryozoa, fecal pellets, and fossil fragments ranging from sparse to packed; some solution enlarged moldic porosity after fossils; ranges from marl to nodular to resistant ledges
--at 15-1/2, 3, 2: iron-stained, bored corrosion surface
--at 6: glauconite, numerous whole Exogyra texana
--at 5-1/2: iron-oxide encrustations on condensed steinkern bed

Punky, former evaporitic horizon?

ERBEN QUARRY SECTION

Located in an abandoned quarry on the Roland Erben ranch off the old river road just below the 4th crossing of the Guadalupe River southeast from the town of Sattler in the northeast portion of the Sattler quadrangle, Comal Co. Section begins in a fault zone inside the apex of the first road bifurcation within the quarry, continues around to the east-southeast, stops, then recontinues northeast across another fault and finishes on the northeastern rim of the quarry.



Pseudosparite to recrystallized oyster fragment biomicrite and fossiliferous intrasparite; other features:
--at 155-157.5, 152-154, 146-149, 141-144: relict bedding with gross units 1 to 6 inches thick but many themselves comprised of 1/8 to 3/4 inch thick beds
--at 149-152: unsorted fossiliferous intrasparite-- a rip-up clast & shell bank with abundant snail steinkerns, miliolids, oysters, Toucasia and clam fragments
--at 149.5, 146: chert nodules

Recrystallization limestone and collapse breccia: formerly sparse biomicrite with dolomitized burrows; thickness of unit varies by several feet due to varying solution collapse; other features:
--at 138.5: chert nodules

Very finely to aphanocrystalline limestone: dense; medium grayish-brown; formerly burrowed very sparse fossil fragment biomicrite; eaten into extensive large megapore channel and cavern system including some collapse brecciation; porosity largely infilled by medium to extremely coarsely crystalline calcite that is often limonite stained; other features:
--at 130: line of section now jumps across a fault trending N28°E (30 ft. throw) and recontinues on northeastern rim of quarry

Thinly bedded, recrystallized intraclastic fossil fragment grainstones & wackestones: lenses and planar laminae from 1/8 to 6 inches thick; from burrowed very sparse biomicrite to sparse oyster biomicrite to sorted oyster-snail intrasparite to jumbled biosparite; dolomitic, especially in burrows; much texture obscured by recrystallization; silica ranges from incipient & complete pervasive to small nodules; nonporous to fair porosity-- some pinpoint and isolated megapore channels; other features:
--at 109-114: caprinid-oyster biolithite with snail steinkerns to very sparse biomicrite

Cherty, recrystallized sparse biomicrite to poorly washed biosparite: burrowed; some thin lensoidal bedding; miliolids, other forams, oyster fragments, clam external molds & fragments, sponge spicules; chert as large bedding elongate nodules to burrow shaped; other features:
--at 100-106: heavily recrystallized; cavernous; speleothemic infill

Finely crystalline dolomite with fossiliferous grainstone: light gray with variable limonite stain; some relict thin bedding-- planar to lensoidal dolomite replacement in sparse biomicrite varies from slight to complete; porosity-- dense nonporous to solution enlarged moldic after fossils to channels to caves; other features:
--at 80.5-84: numerous Toucasia in recrystallized grainstone
--at 79-80.5, 84-91: cavernous with speleothems
--at 76.5-79: thinly bedded planar to lensoidal fossil fragment-intraclastic grainstone; chert nodules shaped like burrows

Finely crystalline dolomite: light gray; moldic porosity after sparse to packed fossils to caves; pulverulite near top with chert nodules

Dolomitized sparse biomicrite: burrowed; miliolids, other forams, oyster & other mollusc fragments; dedolomitized; solution enlarged moldic porosity after fossil fragments and burrows, megapore channels to caves; partial infill by extremely coarsely crystalline calcite; other features:
--at 71-71.5: bedded miliolid intrasparite like unit below

Recrystallized fossiliferous intrasparite: yellowish-beige; thin planar beds (1/16 to 2" thick); miliolids, oyster fragments, clam & snail steinkerns & fragments; some miliolid biomicrite lenses; dedolomitized; other features
--at 60.5-61.5: cavernous collapse breccia; original lith was dolomitized sparse biomicrite; partial infill by red coarsely crystalline calcite

Recrystallized miliolid intrasparite: superficially appears as dense light brownish-gray micrite; planar current laminae (1/8 to 4" thick) locally recognizable; oyster fragments; poorly washed to sorted; some calcite and terra rosa plugged honeycomb porosity; other features:
--at 56-59: possible blue-green algal matting; stylolitic solution condensation; few megapore channels
--at 59: line of section jumps about 1000 feet to southern face of quarry

Covered by quarry fill

Sorted intraclastic miliolid biosparite: few whole high-spired snails; covered interval midway through unit

Covered; some calichified

Intraclastic biomicrite: mottled texture due to large burrows; whitish-brown, dolomitized burrows in medium brown, dolomitic interburrow-- texture identical to Blanco County section; caprinids, Toucasia, clam & snail steinkerns; other features:
--at 16.5: line of section crosses over quarry fill area which may obscure a fault

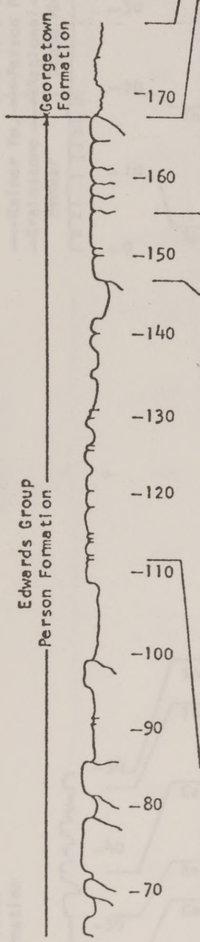
Fossiliferous intrasparite: sorted to unsorted; biomicrite intraclasts; whole snails & clams, forams, large oyster and other fragments; some micritic lenses; rudaceous shell bank

Packed biomicrite: somewhat nodular, burrowed with incipient honeycombing; slightly washed areas; scattered E. texana, abundant snail and clam steinkerns that increase upwards, forams, and fossil fragments

Exogyra texana marl: limonite-stained; burrowed, nodular; silty; whole E. texana, Nerinea, miliolids, in clayey fossil fragment biomicrite; outcrop chewed up in fault zone and abuts Glen Rose

LOOP 337 SOUTH SECTION

Located near the main Balcones fault-line scarp in the northeastern portion of the New Braunfels West quadrangle along Loop 337 South as it skirts the northwestern margin of New Braunfels, Comal Co. Section begins in an abandoned quarry just north of Jentsch Acres then transfers to the fresh roadcuts of Loop 337 South and follows them uphill.



Clayey, sparse fossil-hash biomicrite to clayey sparse oyster biomicrudite: marly to nodular upon weathering; limonite-pervaded; lower levels thoroughly churned and crunched by burrowers; upper horizons have snaggletooth oysters over 3" in diameter, other oysters, clam and snail steinkerns, and serpulids

Toucasia-caprinid biolithite with intraclastic miliolid grainstone and packstone: rudist bank interframework material is sparse to packed biomicrite with intraclastic pelsparite patches; large oysters over 4" in diameter, equant & high-spired snail steinkerns, clam & oyster fragments, rudists and miliolids; slight to fair porosity-- some moldic porosity after caprinids and clams plus some joints; no evidence of recrystallization or the extensive solution and alteration of the underlying units; other features:

- --at 164 - 167: the uppermost Edwards is a 0 to 3 ft. thick rudist mound and poorly washed biosparite to mixed fossil intrasparite; the Edwards-Georgetown contact is a sharp, but weakly developed, bored and iron-stained corrosion surface up on the mound-- however, soft sediment burrows down on the mound flanks carry Georgetown marly biomicrite into the Edwards

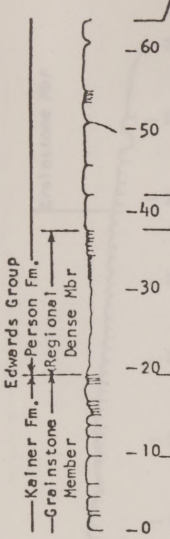
Sparse oyster biomicrudite: slightly recrystallized; burrowed; Gryphaea, forams, clam and other fine fragments; fair to good porosity-- joints created by collapse of underlying beds are now solution enlarged; moldic porosity after fine fossils-- especially in burrows; lithologies getting a "Georgetown" look

Cherty recrystallization limestone, cherty cavernous breccia and cherty recrystallized rudist & oyster fragment wackestone-grainstone: original liths were mostly burrowed sparse miliolid-oyster fragment biomicrite and abundant Toucasia & other fossils in intraclastic biosparite & biomicrite; caprinids, high-spired snails, clams, miliolids, other forams, sponge spicules, and echinoid debris; very cherty interval; most porosity plugged by collapse breccia, travertine, and other calcite infill-- some caverns and megapore channel systems remain; other features:

- --at 142-147: collapse breccia with blocks of cherty fine recrystallization limestone; unit varies in thickness; high interbreccia and megapore channel porosity remains despite limonite-stained medium to extremely coarsely crystalline calcite infill
- --at 139-142, 135.5-138, 128.5-129.5, 124-126, 118.5-122.5: sparse Toucasia-- whole or in fragments; usually occurs with oyster fragments
- --at 135.5-138: collapse horizon-- yellow limonite-pervaded clasts cemented with extremely coarsely crystalline calcite; terra rosa infill
- --at 134.5-135.5: siliceous fine fossil fragment-miliolid grainstone; thinly bedded with sorted to poorly washed layers
- --at 133: chert-- relict texture shows sparse fossil fragment biomicrite clasts in advanced solutionwork process
- --at 126-134.5: cavernous interval-- cherty recrystallization limestone and collapse breccia
- --at 123.5-126: recrystallized, thinly bedded, fine fossil fragment biosparite
- --at 122.5-123.5: condensed interval-- rudaceous clasts and chert nodules in limonitic microsparite
- --at 115-122.5: recrystallized poorly washed, intraclastic rudistid bank talus-- caprinids, Toucasia, clam and snail steinkerns, oyster & other fragments, miliolids & other forams; dense with scattered small megapore channels

Recrystallized sparse biomicrite and collapse breccia: cherty; burrowed; caprinids, Toucasia, large oyster fragments, snails, clams, coral, miliolids, and fossil fragments; former prolific aquifer horizon but now largely plugged by collapse breccia, speleothems, travertine, and laminated terra rosa; solution-condensation is significant-- no single bed carries across the roadcut without having been dissolved away at some spot-- an individual bed also varies laterally from resistant and nonporous to room & pillar type porosity; top & bottom of resistant beds are often strongly etched; other features:

- --at 98-112: unaccessible-- outcrop on upper roadcut face of triangular rock mass
- --at 109-112, 95.5-99, 82-91: chert nodules
- --at 99-109: collapse breccia-- angular blocks (3' x several inches) of failed resistant flagstone
- --at 86-95.5, 64-82: terra rosa-- in laminated pods, as joint fillings, and as infill of megapore channel porosity
- --at 86-95.5: drusy-encrusted breccia interval that condenses to 3 ft. thick on an irregular surface (2 ft. amplitude) marked by terra rosa; midway through unit is distinctive dense yellow-mottled bed
- --at 79-82: collapsed or condensed horizon down to 1 ft. thick
- --at 72.5-79: upper part is caprinid biolithite with large silicified oysters and lower is poorly washed intraclastic biosparite with large oysters, Toucasia, snails and coral; interval condenses to 4 ft. thick and includes pipes filled with encrusted breccia, solution enlarged joints, terra rosa lenses, and travertine
- --at 71.5-72.5, 67-69.5, 64-64.5: drusy encrusted spheres and ovules of recrystallized sparse oyster-fragment biomicrite; infill by coarsely crystalline calcite, travertine, and terra rosa
- --at 69.5-71.5: resistant microsparite that condenses to 6" thick; solution-enlarged joints (5" wide) filled with coated breccia clasts from above and/or with terra rosa; trend of one joint is N-S with 55° dip to E; also contains a 3" diameter cylindrical pipe parallel to bedding



Sparse fossil fragment biomicrite to fine recrystallization limestone: high-spired snails, oyster and clam fragments, ostracods; infilled joints-- small ones with spar, large with terra rosa; mostly dense with slight porosity except for one 5' interval; other features:
--at 63-64, 58, 53.5-55: thin clayey seams
--at 61-61.5: orangish-yellow $CaCO_3$ with sparse fine fossil fragments-- condensation zone varying from 1" to 1' thick
--at 55-61: abundant small gastropods; burrowed
--at 46-51: cavernous fine recrystallization limestone after sparse foram-fossil fragment biomicrite; varying solution-condensation causes thickness of unit to drop to 3' in places; much yellow to reddish-orange calcite infill; excellent porosity remains-- megapore channels and relict moldic porosity after fossil fragments
--at 42-46: sparse oyster biomicrite to partly washed intramicrite; silicified oyster fragments over 4" in diameter; small (1/2 to 1-1/2") irregular chert nodules

Partly washed, intraclastic, fossil fragment biomicrite: rudaceous equant snails, Toucasia, oyster, serpulid and other fossil fragments in dismicritic texture-- bioherm talus?; other features:
--at 42: move around hill and continue section at base of southwestern roadcut of Loop 337 South

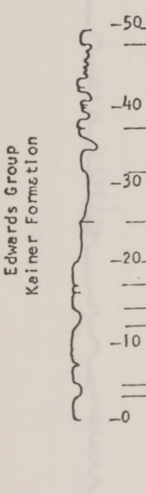
Clayey, sparse, whole mollusc-fossil fragment biomicrite: marly to nodular to massive clayey biomicrite; limonite-stained; wispy clay seams; rudaceous mollusc steinkerns including Pleuromya knowltoni; sparse to very sparse fine fossil hash-- oysters and other molluscs, ostracods, rare miliolids; flaser bedding aspect-- no burrow mottling evident although skeletal debris seems to have been comminuted by scavengers; oxidized pyrite crystals; slight to fair pinpoint porosity; other features:
--at 30: cliff-face above is inaccessible

Thin-bedded, intraclastic biosparite: abundant miliolids, other forams, snail steinkerns, Toucasia, oyster and clam fragments; thin to very thin planar beds and lenses of well sorted grainstone with some of micrite and sparse miliolid biomicrite; abundant micritic intraclasts up to 4" diameter; essentially nonporous; other features:
--at 14.5-16.5: stylolitic
--at 13.8-14.5: sparse fossil fragment biomicrite with wispy clay seams in upper half

Sparse biomicrite: tan; massive; burrow mottled to thoroughly homogenized; sparse to very sparse fossils-- miliolids, some snail steinkerns, fine ostracod and mollusc fragments; slight moldic porosity after fossils; other features:
--at 2-2.5: stylolitic
--at 0-2: some clayey partings

BEAR CREEK ROADCUT SECTION

Located along the new Bear Creek road just south of the Bear Creek fault in the west-central part of the Sattler quadrangle, Comal Co. Section begins at base of east side of roadcut.



Sorted intraclastic biosparite: whitish; loaded with miliolids, other forams, oyster & clam fragments

Thinly bedded fossiliferous intraclastic grainstone to dolomicrite: snail steinkerns & shell fragments; fine laminae and lenses; recrystallized and dedolomitized; current-lensed flags to blue-green algal bound; fenestral porosity and oval megapore vugs to caverns with collapse breccia and terra rosa; intertidal to supratidal

Caprinid biolithite: interframework oyster fragments, snails, clams, & echinoid debris in biomicrite with patchy intrasparite; some recrystallization; caprinids usually go to solution-enlarged moldic porosity; honeycomb and cavernous porosity lensoidally developed; terra rosa infill; chert nodules near top; subtidal

Recrystallization limestone: relict spar-filled moldic porosity after small fossil fragments; honeycombed & cavernous with terra rosa infill

Cavernous dolomite: some dedolomitization; cavernous with speleothems and terra rosa; "original" lith remnants in drusy-covered interchannelway spheres of 1/8 to 1-1/4 inch diameter-- N.B. greatest volume to surface area ratio

Mottled dolomite: unique texture-- anastomosing medium gray mottles in tan dolomite; gray areas contain very coarsely crystalline spar in partially filled intergranular voids; dedolomitization; oyster fragments; moldic porosity after other fossil fragments; drusy-lined megapore vugs

Sparse oyster fragment biomicrite: other fossil fragments; intrasparite patches; some honeycomb porosity with terra rosa infill

Medium crystalline limestone: external molds, spar-filled cavities and solution-enlarged moldic porosity after snails, pelecypod & other fragments; burrow mottled to honeycombed; megapore channels and vugs partly filled with red-stained calcite and terra rosa; top of unit is heavily silicified

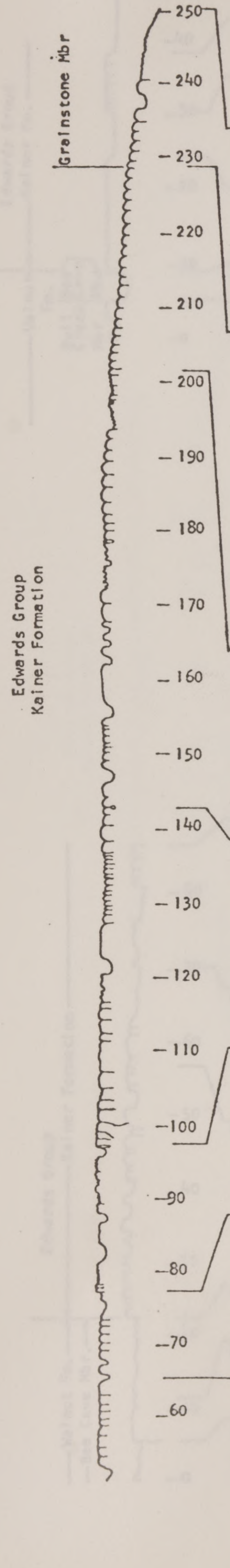
Thinly bedded oyster fragment grainstone to sparse miliolid-mollusc fragment biomicrite to dolomicrite: few burrows; disseminated and nodular chert; other features:
--at 7-7.5: large megapore channels; solution-enlarged moldic porosity after burrows
--at 4.5-5: heavily recrystallized solution collapse interval with chert

Fine to medium recrystallization limestone: solution-enlarged moldic porosity after fossil fragments; irregularly honeycombed-- megapore channels largely filled by red-stained calcite and terra rosa

Recrystallized intraclastic grainstone: dense; beige-gray; oyster fragments, miliolids, clam fragments & external molds; some mottling after burrows; spar-filled tectonic veinlets and solution-enlarged joints common here and throughout the section due to proximity to fault zone

ISAAC CREEK SECTION

Located just northeast of the first crossing of the Guadalupe River near the southeastern corner of the Sattler quadrangle, Comal Co. Section begins at juncture of Isaac Creek and the Guadalupe River, works its way north, and then east to the top of a hill with a spot elevation of 905 ft. This is close to the section measured by A. Peter Noyes, Jr. (1957) and Terry V. Bills, Jr. (1957).



Sorted miliolid biosparite to unsorted miliolid intrasparite: abundant miliolids, other forams, Nerinea, Monopleura, oyster and other fragments; micritic intraclasts; slight moldic porosity after fossils; other features:
--at 250: gently convex calichified marl surface-- probably residue from Regional Dense Member
--at 249-250: float blocks of silicified Monopleura
--at 240.5-243.5, 236.5-238.5: covered

Fine to very coarse pseudosparite: grayish-white; slight vuggy porosity; flattish slope allowed weathering to virtually obliterate any depositional textures

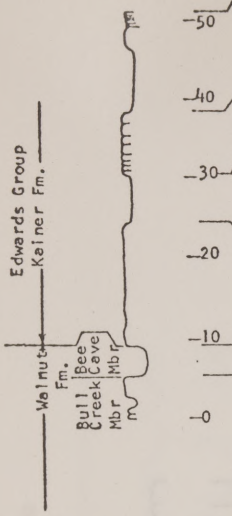
Recrystallization limestone with some weathered dolomitized biomicrite-biosparite: relict miliolids, oyster and other fragments, Toucasia; some thin bedding shows on weathered surfaces; nonporous to cavernous-- many large megapore vugs elongate parallel to bedding, moldic after fossils, intercrystalline, and megapore channels; other features:
--at 197.5-198.5: relict thin laminae with leached miliolids
--at 194.5-195, 151.5-152.5: stromatolitic
--at 191-192.5, 157-162, 154.5-155: miliolid-fossil fragment biosparite
--at 178.5: chert nodules
--at 174.5-175.5, 165.5-166.5, 164-164.5, 162-163, 155.5-156.5, 146-148: covered
--at 172.5-173.5: silicified Toucasia biolithite

Intraclastic miliolid-fossil fragment grainstone: recrystallization and weathering have obscured the original texture-- apparently mostly muddy biosparite; many intervals show thin lenses and planar beds; loaded with miliolids, oyster and clam fragments, snail steinkerns, rudists, abundant fine fossil fragments; intraclasts are micrite and sparse biomicrite; some dolomitic horizons; porosity varies from slight to cavernous-- solution enlarged moldic after fossils, honeycombing, large megapore vugs, and fenestral after planar-lensoidal laminae; other features:
--at 143: chert nodules packed with miliolids, small oyster and other fragments; also relict dolomitized burrow
--at 122.5-127.5: caprinid biolithite with interframework recrystallized sparse fossil fragment biomicrite
--at 120.5-122.5: covered

Recrystallized, sparse fossil fragment biomicrite: burrowed; small snail steinkerns, mollusc fragments; honeycomb porosity developed through solution-removal of burrow fill; other features:
--at 97.5: iron-stained, pinch and swell chert layer
--at 96-97.5: cavernous
--at 89.5-92.5: burrowed biomicrite overlain by slightly burrowed, partly washed biomicrite overlain by current bedded fossiliferous grainstone and micrite laminae-- a shallowing upward tidal sequence
--at 86.5-87.5, 81.5-84: covered, recessive intervals
--at 77.5-78.5: flaser bedding

Finely crystalline dolomite and dolomitized sparse biomicrite: oyster fragments, miliolids, high-spired snail steinkerns, mollusc debris; fair to good porosity-- intercrystalline and moldic after fossils; other features:
--at 75.5-77.5: disseminated bluish chert in dolomitized sparse biomicrite with oyster and other fossil fragments
--at 75: light gray chert nodules
--at 73.5-75: contains crinkly bedding reminiscent of Cyanophyta
--at 72.5-73.5: unsorted gastropod intrasparite; intraclasts of micrite and sparse biomicrite but also intrasparite

Poorly washed intraclastic miliolid biosparite with some sparse biomicrite: abundant miliolids, large snail steinkerns, clams-whole and fragments; intraclasts of micrite and sparse biomicrite; slight to fair porosity-- solution enlarged moldic after clams and fossil fragments on up to large megapore vugs; other features:
--at 52-53.5: pulverulitic dolomite



Fine to medium crystalline dolomite: thinly bedded, planar to lensoidal; oyster, clam and other fine fossil fragments, some snail steinkerns, forams; fair porosity-- intercrystalline and moldic; other features:
--at 49.5-51: outcrop feel is grainstone but dolomitization and weathering have obscured original texture
--at 45-46.5: nonporous microsparite

Sorted intraclastic miliolid grainstone: weathered; ledgy; whitish; miliolids, small oyster and clam fragments; small micritic intraclasts; slight porosity; other features:
--at 35.5-37: burrowed; honeycomb porosity

Finely crystalline dolomite to aggregate of recrystallization limestone spheres: former cavernous horizon-- initially all finely crystalline dolomite with fair to good intercrystalline porosity; groundwater concentration in some spots created mass of recrystallized spherical balls; porosity now largely infilled by calcite crystals; porosity history evident in stream cutbanks but virtually unrecognizable on hillslopes due to caliche plugging and covering by monotonous light gray weathering patina

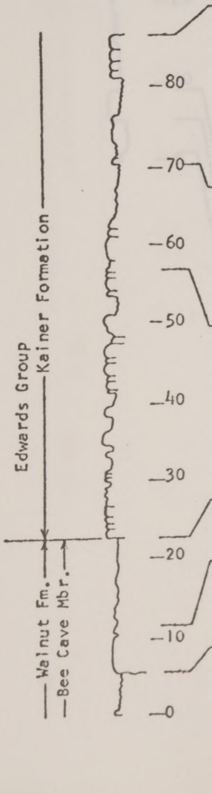
Dolomitized caprinid biolithite and sparse biomicrite: areas of burrowed biomicrite then patches rich in caprinids; pervasive dolomite is finely crystalline; oyster fragments, whole clams and snails; fair porosity-- intercrystalline to moldic after snails, clams, caprinids, and fossil fragments

Exogyra texana marl: weakly resistant-- recessed back under overhanging cliff; E. texana valves in placers and disseminated

Intraclastic Nerinea -miliolid biosparite: grayish-white dolomitized soft burrows in orangish-brown limestone; moderately sorted; other features:
--at 5: corrosion surface-- iron-stained bored surface with Exogyra texana valves affixed
--at 1-2: covered
--at 0.5-1: dolomitized fossil fragment biosparite; good porosity-- intercrystalline and moldic after fossils
--at 0-0.5: intraclastic oyster biosparite

VALLEY VIEW SECTION

Located in the southeastern portion of the Smithson Valley quadrangle near the intersection of Highway 46 and Crane's Mill Road where a lone dwelling is designated as the town of Valley View. Section begins in the bed of Dry Comal Creek just south of Highway 46, works its way southwest up a stream cutbank, and then west along the highway's southern roadcut.



Cherty biomicrite, pseudosparite, grainstone and dolomite: other features:
--at 84.5-86.5: light gray, finely crystalline dolomite after burrowed, sparse, small clam-foram-fossil fragment biomicrite; moldic porosity after clams and fossil fragments
--at 81-84.5: cherty, sorted shell placer-- miliolid-oyster fragment grainstone; good intergranular porosity
--at 76.5-81: cavernous fine recrystallization limestone; also with solution enlarged moldic porosity after clams and fossil fragments
--at 70-76.5: cherty, thinly bedded lenses of sparse to packed oyster fragment biomicrite and some intraclastic biosparite

Cavernous, fine recrystallization limestone: undigested patches of sparse fossil fragment biomicrite; excellent porosity-- megapore vugs hinting at former presence of clams and snails, megapore channels after burrows, fenestral, and caverns; some travertine and drusy calcite infill; other features:
--at 59.5: irregular chert nodules up to 1/2 ft. diameter
--at 58-60.5: sparse biomicrite with rudaceous Toucasia and Gryphaea, snails, and fossils fragments
--at 56.5-58: pervasively silicified pseudosparite

Sorted, intraclastic, miliolid-fossil fragment biosparite to sparse fossil fragment biomicrite: primary texture obscured by weathering; fossil fragments are primarily oysters and other molluscs; whole clam and snail steinkerns in some intervals; other features:
--at 53-56.5, 22.5-25: thin planar beds
--at 50-53, 36.5-38, 33.5-34.5, 31.5-33, 29-30: recessive and covered; caliche-impregnated beds on the hillside appear overly thick because of swelling-- roadcuts show "synclinal" structure due to expansive swelling near each natural hillside
--at 43.5-47.5, 38-39, 34.5-36.5, 25-26.5: honeycomb weathering apparently after caprinids or burrows

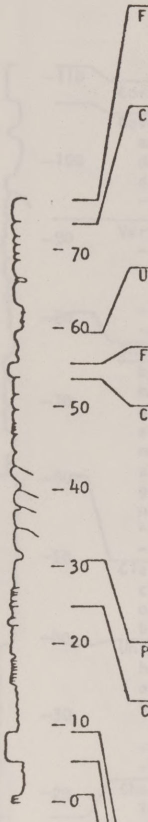
Finely crystalline dolomite: orangish-gray; punky; good porosity-- solution enlarged moldic after small fossil fragments and intercrystalline; other features:
--at 14-16, 18-22.5: covered and/or calichified

Dolomitic mollusc biomicrite to biosparite: jumbled to sorted, unwashed to washed lenses and layers of Exogyra texana, Gryphaea-like oysters, diverse rudaceous clam & snail steinkerns, miliolids, ammonites, echinoid debris, worm tubes, and abundant fragments; dolomite increases upward-- especially affects burrows, clams and snails; some moldic porosity after clams

Sandy, Exogyra texana marl: elongate nodules; almost fissile in places; remains of diverse molluscs-- E. texana, pectens, snail & clam steinkerns, and fragments; echinoid debris; quarried for road metal; other features:
--at 0-0.5: sorted, sandy, oolitic intrasparite with abundant mollusc fragments

SERVTEX MATERIALS CO. QUARRY SECTION

Locality is in the lower (eastern) quarry of the Servtex Materials Co. along the main Balcones fault-line scarp in the southeastern part of the Bat Cave quadrangle, Comal Co. Section begins on the west side, switches east and down across a sharp flexure, and then samples the two working levels on the eastern face. The upper part of the lower level is physically inaccessible and was sampled by throwing rocks against the quarry wall. This is essentially the same section measured by John Newcomb (1971).



Edwards Group
Person Formation

Fine recrystallization limestone: sparse silicified fossil fragments include oysters, pectens and echinoid spines; abundant branching tubules of burrow-shaped chert; the overlying beds are visible on the working faces of the active upper (western) quarry-- lithologies appear to be cherty grainstones and cherty Toucasia-caprinid beds with enlarged moldic porosity but without cavernous horizons

Cherty recrystallized caprinid-Toucasia biolithites and intraclastic biosparite: elongate chert nodules (up to 3 ft. long) parallel to bedding occur throughout; moldic porosity after caprinids, clams and some fossil fragments; other features:
- --at 69-73.5: bedded microcoquina to unsorted intraclastic biosparite: packed with miliolids, other forams and small fossil fragments; intraclastic beds have caprinids, clams, snails and oyster fragments; good intergranular porosity and moldic after fossils
- --at 62.5-69: biolithites and associated debris-- abundant caprinids, Toucasia, silicified Gryphaea-like oysters, clam & snail steinkerns, miliolids and fossil fragments

Unsorted intraclastic biosparite: planar beds and lenses of grainstone; extensive small megapore channel porosity developed on fenestral plan due to control of original bedding; clear to porcellanous, drusy to speleothemic calcite is partial infilling

Fine recrystallization limestone: Toucasia fragments, large (2+ ") silicified oyster fragments; solution enlarged moldic porosity after caprinids, clams and fossil fragments; other features:
- --at 55.5: floor of upper level at eastern edge of quarry

Cavernous, cherty recrystallization limestone and collapse breccia: little original texture remains-- Toucasia, some solution enlarged moldic porosity after clams and fossil fragments, and similar fossils plus oysters in chert; some beds are an aggregate of drusy enveloped spheres of fine to medium recrystallization limestone-- sphere diameters range from 1/2 to 1-1/2 inches diameter with excellent intersphere porosity; other porosity types are fenestral, channels and caverns; this unit is highly cavernous with profuse speleothems, travertine, terra rosa, collapse breccia and condensed zones-- different horizons are cavernous in varying parts of the quarry-- the western (upwarped) side has only a few highly porous zones, the eastern (downwarped) has many, but the northern face (below a pre-quarry creek) has maximum cavern development with laminated terra rosa infill that has yielded Pleistocene vertebrate remains; numerous Toucasia; abundant chert-- oddly shaped and elongate nodules parallel to bedding except where collapse has occurred

Poorly washed intraclastic biopelsparite to sparse fossil fragment biomicrite: snail steinkerns, oyster fragments, clam external molds; unsorted intraclastic-pelletal-fossiliferous packstone below increases in burrows, comminuted shell debris and micrite upwards

Clayey sparse biomicrite (marl) to dolomitic, poorly washed, intraclastic biopelsparite; other features:
- --at 18.5-25: burrowed, clayey sparse biomicrite; wispy clay seams; some Nerinea steinkerns and numerous oyster fragments at some horizons; some burrows dissolved out to form fair-good, meso-to megapore channels
- --at 18-18.5, 9-15.5: clayey, very sparse biomicrite to calcareous claystone; wispy clay seams surrounding carbonate-rich nodules impart a flaser bedding aspect
- --at 15.5-18: dolomitic, burrowed, poorly washed intraclastic biopelsparite; high-spired snail steinkerns, ostracods; dolomitized burrows; abundant micritic intraclasts and pellets

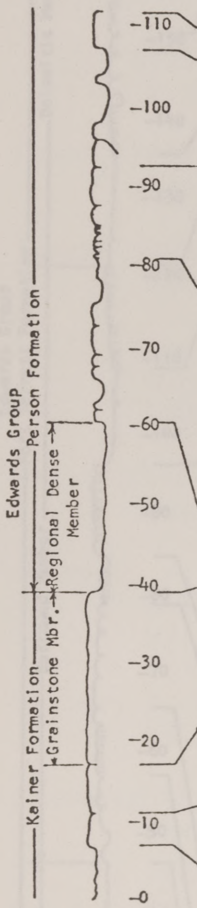
Dolomitic Toucasia biolithite and rubble: typical interframework texture-- sparse fossil fragment biomicrite with pectens varying to partly washed intraclastic-pelletal patches; unit forms floor for eastern (downflexure) side of lower quarry

Fine recrystallization limestone: excellent porosity-- anastomosing meso-to megapore channels; lower 3/4 of unit is covered

Dolomitic sparse biomicrite to sorted biosparite: flaggy beds; lower half is dolomitic, sparse to slightly washed miliolid-Dictyoconus-fossil fragment biomicrite overlain by 1/2 inch of clay-seamed biomicrite; next is burrowed sparse miliolid-fossil fragment biomicrite with some dismicritic texture suggestive of Cyanophyta; upper flagstone is sorted miliolid-pelecypod fragment biosparite; these flaggy beds have been stripped of overburden to form a domed working floor for the western side of the lower quarry

U. S. GYPSUM CO. QUARRY SECTION

Located within the large U. S. Gypsum Co. quarry along the main Balcones fault-line scarp in the center of the New Braunfels West quadrangle at Dittlinger, Comal Co. The section was measured in a lowermost pit, and the four working levels above it, in the east-central part of the quarry. The 22 ft. thick grainstone member of the Kainer Formation is the only rock unit utilized by the company.



Coral-Toucasia-oyster biolithite: abundant chertified coralline masses over 1 foot in diameter

Cavernous, finely crystalline limestone: recrystallized sparse fossil fragment biomicrite; cavernous and large megapore channel porosity still remains though most porosity in interval has been destroyed by speleothems, yellow limonite-stained travertine, dense limonitic and clear calcite drusy, and terra rosa; other features:
- --at 92.5-96: Toucasia fragments in residual recrystallization limestone spheres

Very sparse biomicrite and medium crystalline limestone; other features:
- --at 81-81.5: flaser bedded sparse oyster fragment biomicrite
- --at 81.5-84: mottled medium crystalline limestone with intraclast ghosts; megapore channels partly infilled by drusy calcite
- --at 84-85: clayey stringers in limonitic very sparse biomicrite
- --at 85-92.5: sparse biomicrite with porous fossil fragment-filled burrows

Toucasia-caprinid-oyster biolithite & biomicrite and cavernous recrystallization limestone: biolithites have characteristic poorly washed-dismicritic-intraclastic appearing interframework matrix containing oyster & clam fragments, snail steinkerns, corals, and fossil hash; some fossils are silicified, especially oysters; interval in middle of unit has 1 ft. diam. thin oysters as encountered below; fine-medium crystalline limestone intervals formerly dissolved into large megapore channel & cavern systems now largely infilled by coarse to extremely coarse crystalline calcite, limonitic travertine, dense yellow aphanocrystalline calcite, and terra rosa; still has good porosity-- small caverns, mesopore-megapore channels, and fenestral vugs; small chert nodules; other features:
- --at 63: third level in quarry
- --at 80: fourth level in quarry

Clayey, very sparse fossil fragment biomicrite to sparse mollusc biomicrite; orangish-tan; characteristic Pleuromya knowltoni steinkerns; flaser bedding with elongate fossil fragments oriented subparallel to bedding; occasional thin small lenses or patches of intraclastic biosparite-biomicrite; fair pinpoint porosity

Unsorted to poorly washed oolitic and intraclastic biosparite: abundant miliolids, other forams, high-spired snail steinkerns and pelecypod fragments; bedding-- 6" to 3' thick; minor porosity and stylolites; other features:
- --at 17-24: some thin micrite lenses and burrowed, sparse miliolid-fossil fragment biomicrite layers with pelsparite patches
- --at 32: clayey layer
- --at 39: second level in quarry

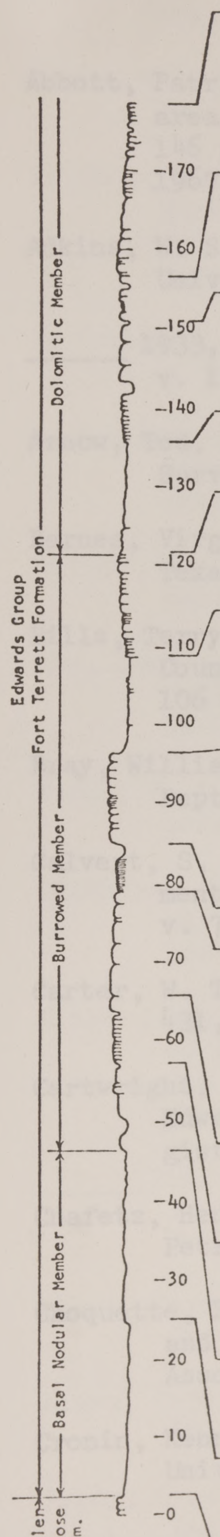
Cherty, poorly-washed, rudist-oyster biosparrudite: abundant dish-like oysters (1 ft. diam. & 1/4 inch thick), caprinids, Toucasia, clam external molds and small fossil fragments; matrix slightly recrystallized; fair porosity-- moldic after caprinids and some mesopore vugs; other features:
- --at 17: main floor of quarry

Cherty, recrystallized, dolomitic micrite and grainstone; bedding from 1/16" to 1" thick; oval chert pipe (11" x 2" x 3") parallel to bedding in intraclastic grainstone layer-- tripoli rind shows small whole clams and snails with oolite-like grains

Recrystallization limestone, secondary calcite infill, and terra rosa: less than 10% porosity remains; other features:
- --at 4: highly angular, unsorted, collapse breccia intrasparite-- texturally identical to the collapse breccias of the Kirschberg evaporite member in the Turkey Knob section

WEST SISTER CREEK SECTION

Located along State Highway 1376 about nine miles north of Sisterdale, Kendall Co. Section measured in the roadcuts rising north out of the West Sister Creek valley. The location of this section is identical to that of Pete Rose (1968).



Cherty, medium crystalline dolomite: tan to medium gray; mainly high intertidal to supratidal deposits--evidenced by dolomitization, collapse breccia, shell placers with abundant Nerinea and miliolids, dolomite crystals growing into voids, thin planar to lenticular beds with some low angle crossbeds, lack of burrows, and vugular porosity after evaporite nodules; good porosity--intercrystalline, vugular, breccia, and moldic after fossils; other features:
--at 174-174.5: pulverulite
--at 173, 170.5, 167.5, 166.5, 160.5-165.5: chert
--at 170.5-171.5: dolomitized collapse breccia

Intraclastic biosparite: thinly bedded and flaggy; sorted biosparite to unsorted miliolid intrasparite; micrite intraclasts; oysters, snails, clam fragments, miliolids and other forams; nonporous; other features:
--at 155-155.5: pulverulite
--at 153-154: sorted high-spired gastropod biosparite-- tidal channel deposit
--at 152: light gray chert nodules (2' x 1/2")

Fine to medium crystalline dolomite: medium gray; thinly bedded below-to massive above: good porosity-- intercrystalline and moldic after fossils; other features:
--at 143.5-151: medium crystalline dolomite after sparse whole mollusc-miliolid biomicrite
--at 141.5-143.5: pulverulitic dolomite
--at 135.5-141.5: laminar to thinly bedded lithologies include oyster biomicrudite; micrite; intraclastic miliolid grainstone; dolomicrite; and finely crystalline dolomite

Dolomitic, burrowed sparse biomicrite: striking texture--medium gray dolomitized burrows in whitish-beige sparse biomicrite; burrows are large, filled with medium crystalline dolomite, and have good intercrystalline and moldic porosity after comminuted fossils; oysters, forams, mollusc and other fossil fragments

Bedded dolomite with sparse biomicrite: flaggy interval-- commonly wavy to planar laminae, very thin bedded planar, or flaser bedded; mostly finely crystalline dolomite after current-bedded, intraclastic sparse to partly washed biomicrite or micrite; some burrows--usually with greater porosity and dolomite content; fair to good porosity-- intercrystalline and moldic after miliolids, snails, mollusc and other fragments; other features:
--at 121.5-122: oyster biomicrudite interbedded with clayey micrite

Finely crystalline dolomite to sparse biomicrite: weakly resistant; fair to good pinpoint porosity; transitional upward from dolomite to sparse biomicrite; other features:
--at 104.5-108.5: chalky weathered appearance clouds burrowed sparse biomicrite containing pectens and small oyster & clam fragments
--at 100-104.5: dolomitic, sparse fossil fragment biomicrite with flaser bedding; a few burrows
--at 96.5-100: dolomite; good porosity-- intercrystalline and moldic after small whole snails & clams, miliolids and dasyclad algae

Poorly washed biosparite to packed biomicrite: burrowed; original texture obscured by weathering; miliolids, high-spired snails, whole clams, oysters and other fragments; fair to good porosity--pinpoint where weathered, honeycomb or moldic after burrows, and some moldic after fossils; other features:
--at 95.5-96.5: moderately dolomitized-- transitional to unit above
--at 91-95.5: cherty-- includes string of elongate parallel to bedding nodules at 93.5
--at 89.5-91: flaggy interval-- laminated to very thinly bedded intraclastic fossiliferous grainstone-- some stromatolites

Finely crystalline dolomite: punky, finely laminated to wavy bedded dolomite overlain by calichified pulverulite; good porosity-- intercrystalline

Cherty sparse biomicrite to biosparite: weathering has produced a chalky aspect that obscures original textures; burrowed; abundant miliolids, clams, bryozoa, and fossil fragments; much of interval may have been intraclastic miliolid grainstone; fair to good porosity-- pinpoint porosity in weathered matrix and some honeycomb porosity where burrows have been leached out; other features:
--at 78.5, 77.5, 69.5-75: chert nodules-- from small and irregular to foot-long, elongate parallel to bedding
--at 75, 69.5: pronounced iron-stained surface
--at 68-69.5: Monopleura patch reefs with Nerinea, pectens, whole clams and large oysters in burrowed sparse fossil fragment biomicrite matrix

Finely crystalline dolomite: supratidal dolomite package-- evidenced by very thin bedding, stromatolites, dessication cracks, relict intraclasts, large megapore vugs after presumed anhydrite-gypsum nodules, common hieroglyph-shaped porosity after roots? or thin worm burrows? or gypsum crystals?, thin dolomite crusts, and birdseye texture; good porosity-- intercrystalline and moldic after microfossils, gypsum crystals, and roots

Dolomitized rudist biolithites and burrowed biomicrites: banks built by caprinid-Toucasia or Monopleura with serpulids: distinctive medium brown burrows in light beige biomicrite-- same texture found at this stratigraphic level in Blanco and Comal Counties; sparse to packed to partly washed biomicrite matrix contains rudists, equant snails, clams, pectens, miliolids, other forams, oysters and fine fossil fragments; dolomite is finely crystalline; fair porosity--intercrystalline and moldic after fossils

Monopleura biolithite and sparse biomicrite: original textures obscured by calichification; some terrigenous mud admixture; Toucasia, pectens, whole clams and snails, oysters, and fossil fragments; other features:
--at 46: eyelevel across small valley and recontinue on northern side
--at 24.5-29: sandy, nodular marl with abundant fossils-- diverse molluscs

Silty marl to calcareous claystone: basal few feet is calichified clayey dolomite followed by distinctive greenish, non-fissile claystone-- no evident megafossils; upper several feet is silty marl and clayey sparse Exogyra texana biomicrite; this unit occupies the geometric position of the Walnut Formation which it resembles with its quartz silt and Exogyra texana-- the fundamental difference is the greatly increased percentage of terrigenous clay

Finely crystalline dolomite: clayey, punky, unidentifiable relict allochems; good porosity--mostly intercrystalline but some laminae with moldic after small forams and fossil fragments

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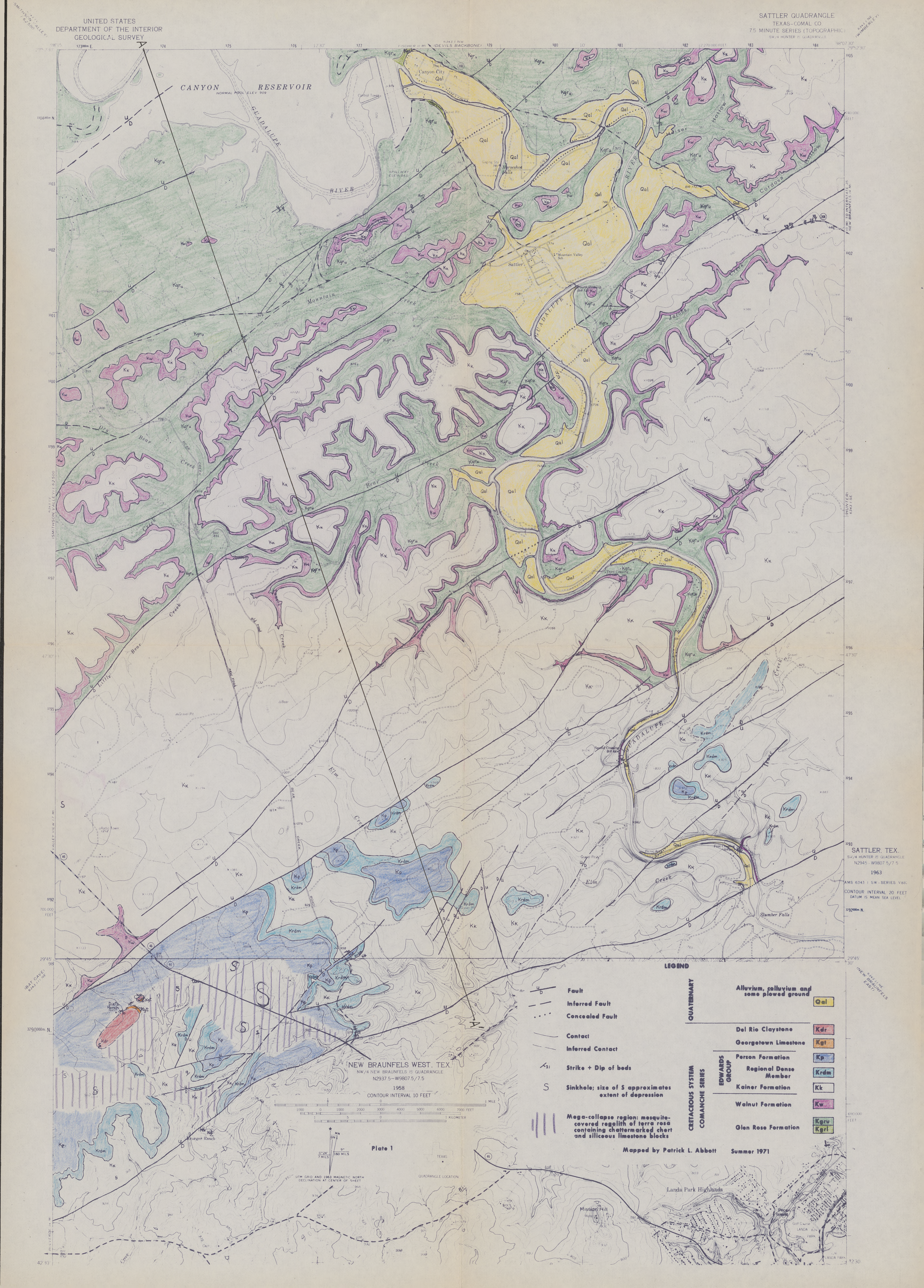
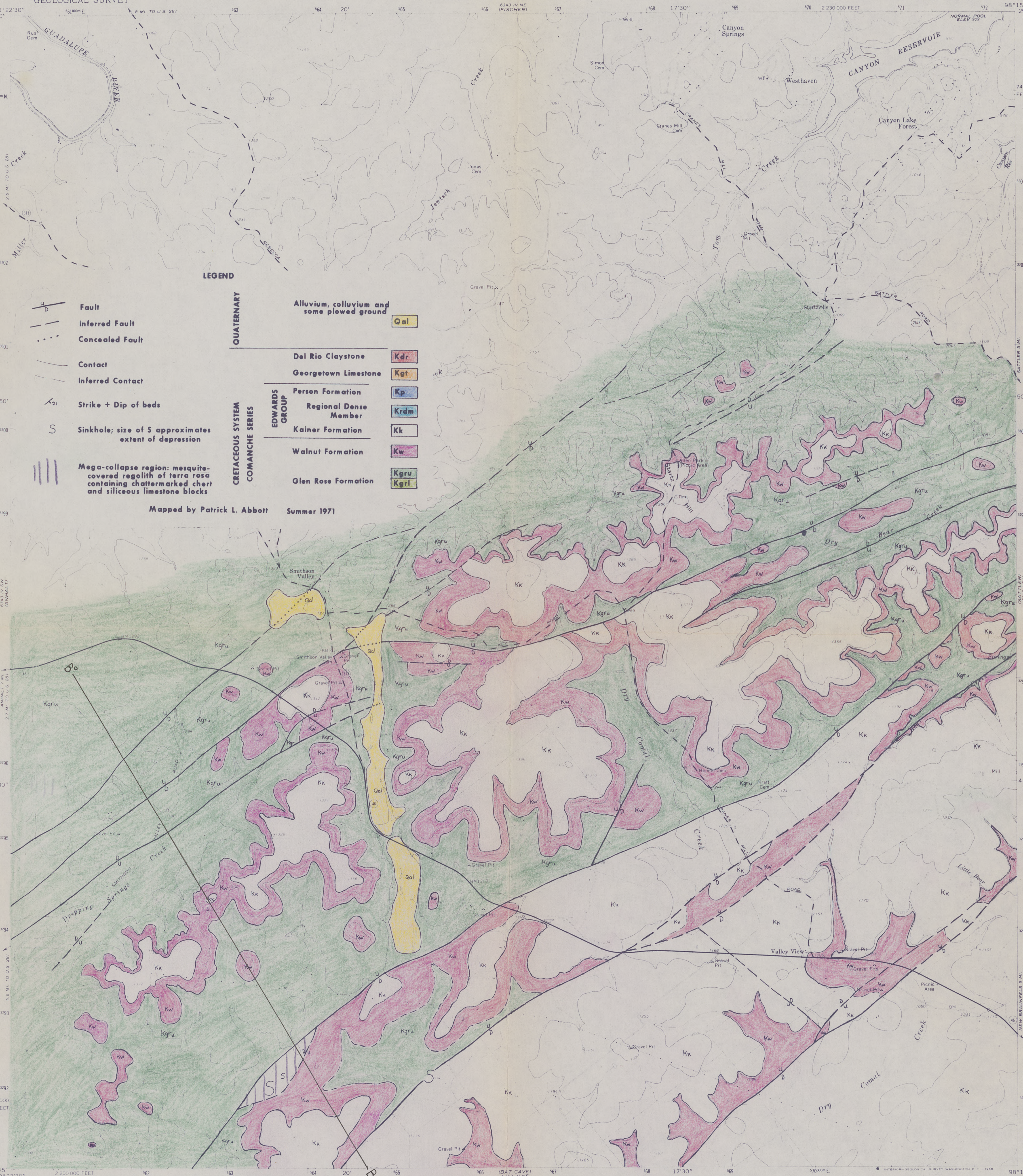


UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
SATTLER QUADRANGLE
TEXAS–COMAL CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)
CANYON RESERVOIR
GUADALUPE
RIVER
Canyon City
Horseshoe Falls
Sattler
Mountain Valley Sch.
Mountain Creek
Dry Bear Creek
Bear Creek
Little Bear Creek
Elm Creek
Jacobs Creek
Cordova Hollow
Slumber Falls
SATTLER, TEX.
1963
CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL
NEW BRAUNFELS WEST, TEX.
NW/4 NEW BRAUNFELS 15' QUADRANGLE
N2937.5—W9807.5/7.5
1958
CONTOUR INTERVAL 10 FEET
Plate 1
QUADRANGLE LOCATION
Landa Park Highlands
Mission Hill
LEGEND
Fault
Inferred Fault
Concealed Fault
Contact
Inferred Contact
Strike + Dip of beds
Sinkhole; size of S approximates extent of depression
Mega-collapse region: mesquite-covered regolith of terra rosa containing chattermarked chert and siliceous limestone blocks
QUATERNARY
Alluvium, colluvium and some plowed ground
Qal
CRETACEOUS SYSTEM
COMANCHE SERIES
Del Rio Claystone
Kdr
Georgetown Limestone
Kgt
EDWARDS GROUP
Person Formation
Kp
Regional Dense Member
Krdm
Kainer Formation
Kk
Walnut Formation
Kw
Glen Rose Formation
Kgru
Kgrl
Mapped by Patrick L. Abbott Summer 1971

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

STATE OF TEXAS
TEXAS WATER DEVELOPMENT BOARD

SMITHSON VALLEY QUADRANGLE
TEXAS–COMAL CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)
SE/4 SMITHSON VALLEY 15' QUADRANGLE



Control by USGS and USC&GS

Topography by photogrammetric methods from aerial photographs taken 1963. Field checked 1964

Polyconic projection. 1927 North American datum
10,000-foot grid based on Texas coordinate system, south central zone
1000-meter Universal Transverse Mercator grid ticks, zone 14, shown in blue

Fine red dashed lines indicate selected fence lines

Areas covered by dashed light-blue pattern are subject to controlled inundation

UTM GRID AND 1964 MAGNETIC NORTH
DECLINATION AT CENTER OF SHEET

CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL

QUADRANGLE LOCATION

ROAD CLASSIFICATION
Heavy-duty | Light-duty
Medium-duty | Unimproved dirt
State Route

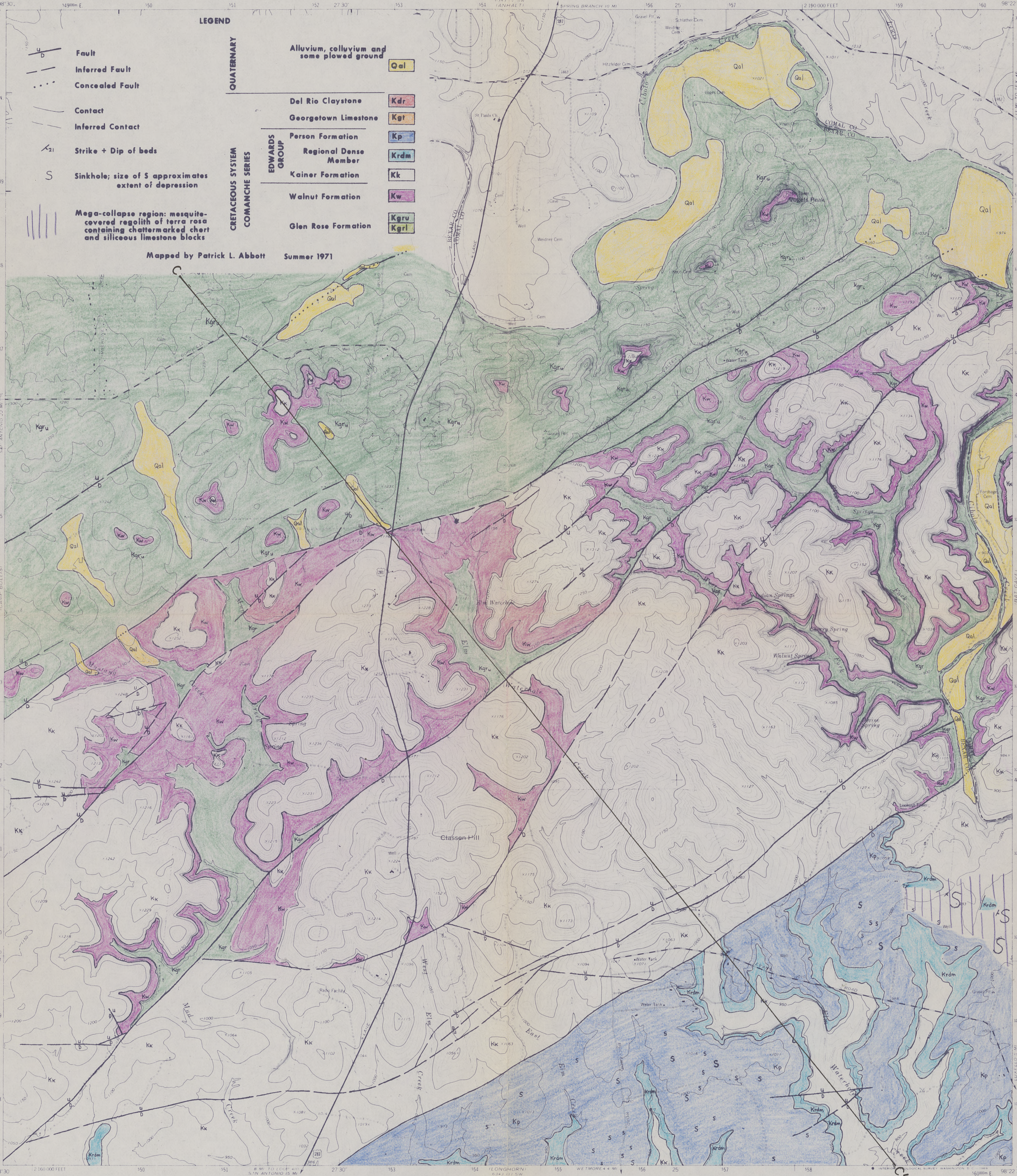
Plate 2 SMITHSON VALLEY, TEX.
SE/4 SMITHSON VALLEY 15' QUADRANGLE
N2945—W9815/7.5

1964

AMS 6343 IV SE–SERIES V882

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

BULVERDE QUADRANGLE
TEXAS
7.5 MINUTE SERIES (TOPOGRAPHIC)



CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

QUADRANGLE LOCATION

ROAD CLASSIFICATION

Heavy-duty
Light-duty
Medium-duty
Unimproved dirt
U. S. Route
State Route

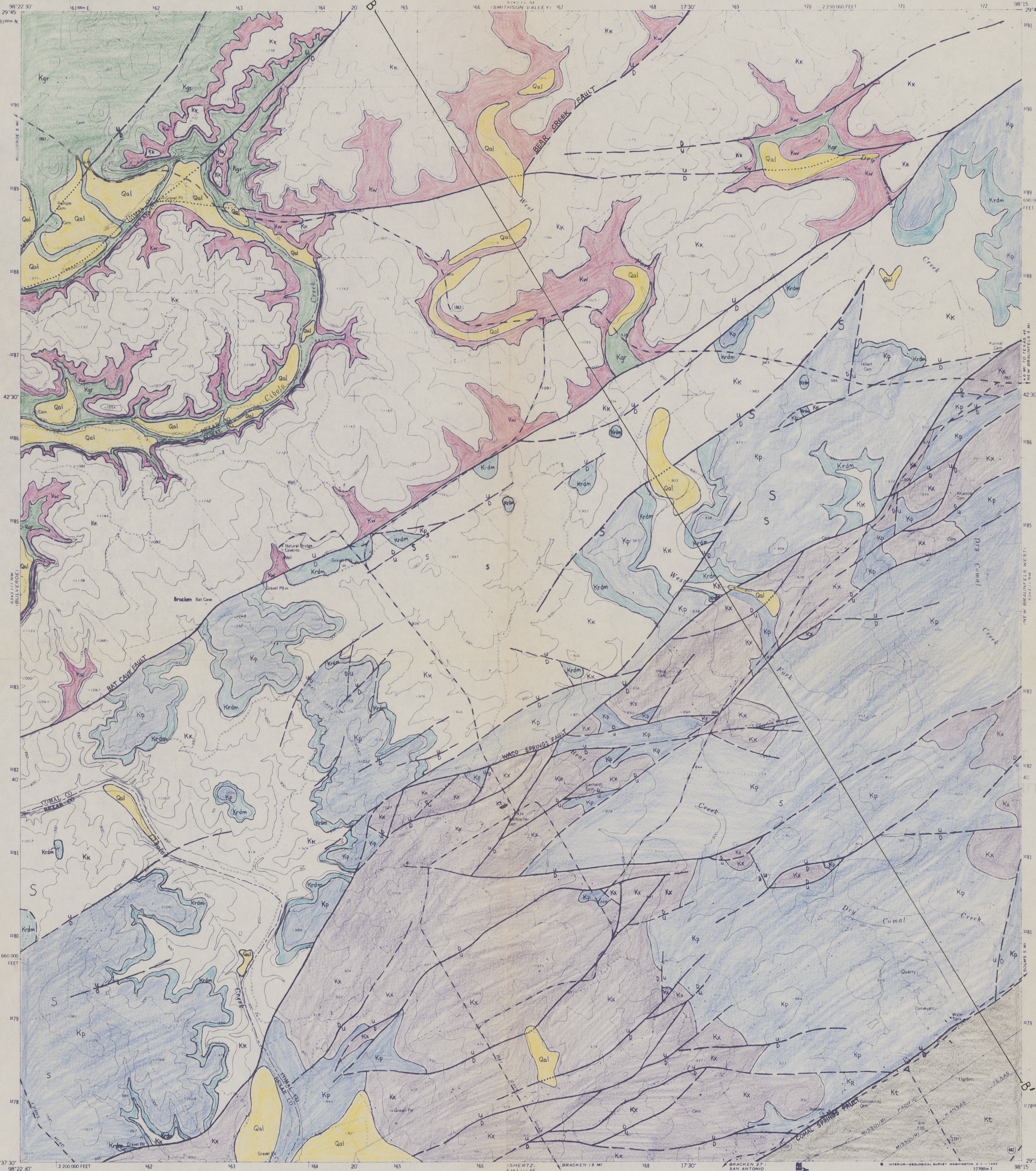
Plate3 BULVERDE, TEX.
N2937.5-W9822.5/7.5

1967

AMS 6543 III NW SERIES V882

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

BAT CAVE QUADRANGLE
TEXAS
7.5 MINUTE SERIES (TOPOGRAPHIC)



Fault

Inferred Fault

Concealed Fault

Contact

Inferred Contact

Strike + Dip of beds

S Sinkhole; size of S approximates extent of depression

UTM GRID AND 1967 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

QUADRANGLE LOCATION

CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL

MAPPED by JOHN H. NEWCOMB Spring 1970

Adapted by Patrick L. Abbott

Plate 4 BAT CAVE, TEX.
N2937.5—W9815/7.5
1967

QUATERNARY		Alluvium, colluvium and some plowed ground	Qal
CRETACEOUS SYSTEM	GULF SERIES	Taylor Clay	Kt
		Austin Chalk Eagle Ford Formation	
	COMANCHE SERIES	Buda Limestone Del Rio Claystone Georgetown Limestone	Kx
	EDWARDS GROUP	Person Formation	Kp
		Regional Dense Member	Krdm
		Kainer Formation	Kk
		Walnut Formation	Kw
		Glen Rose Formation	Kgr

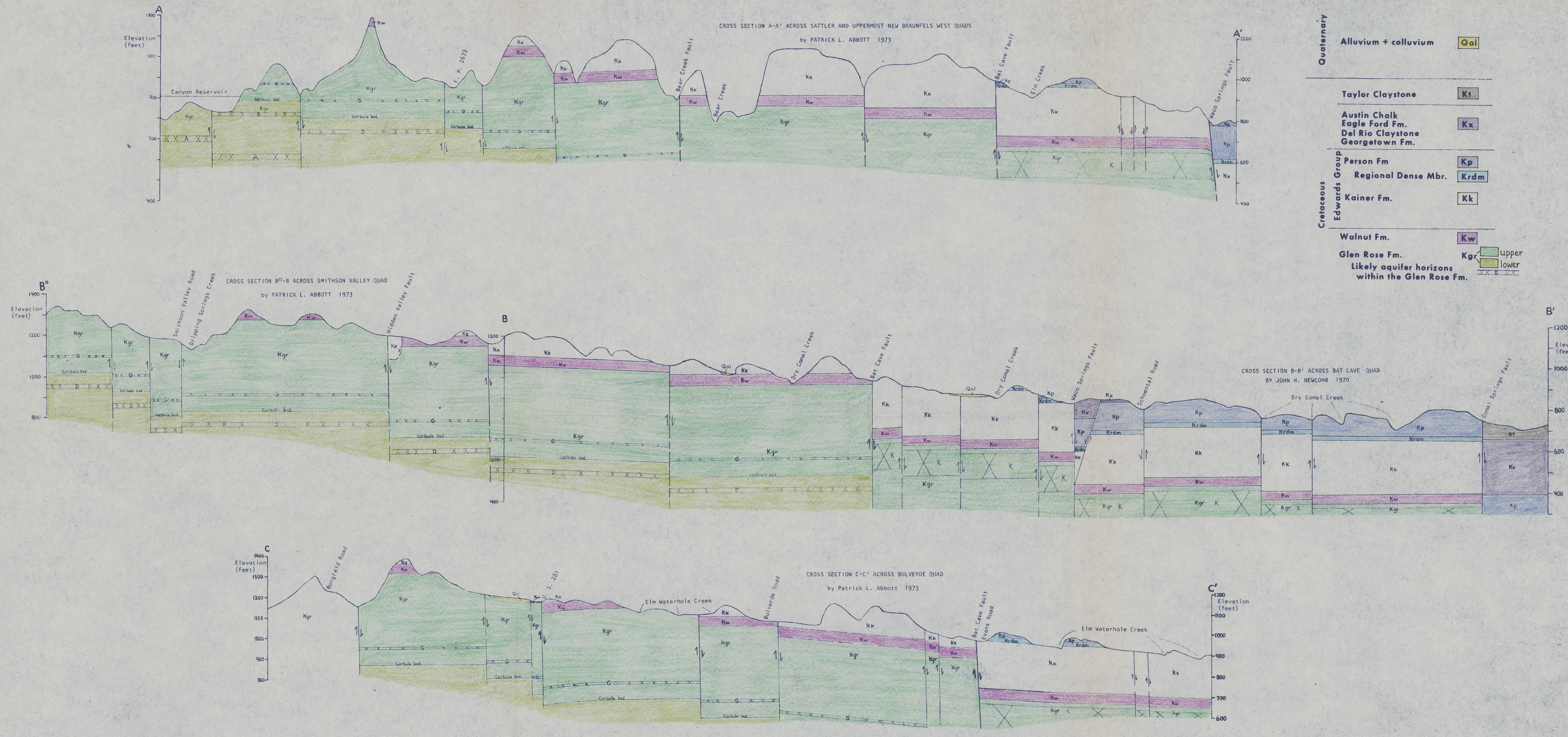


PLATE 5 CROSS SECTIONS FOR PLATES 1,2,3,4

by Patrick L. Abbott 1973

0 1000 2000 3000 4000 5000 feet

Horizontal Scale

VERTICAL EXAGGERATION 10X

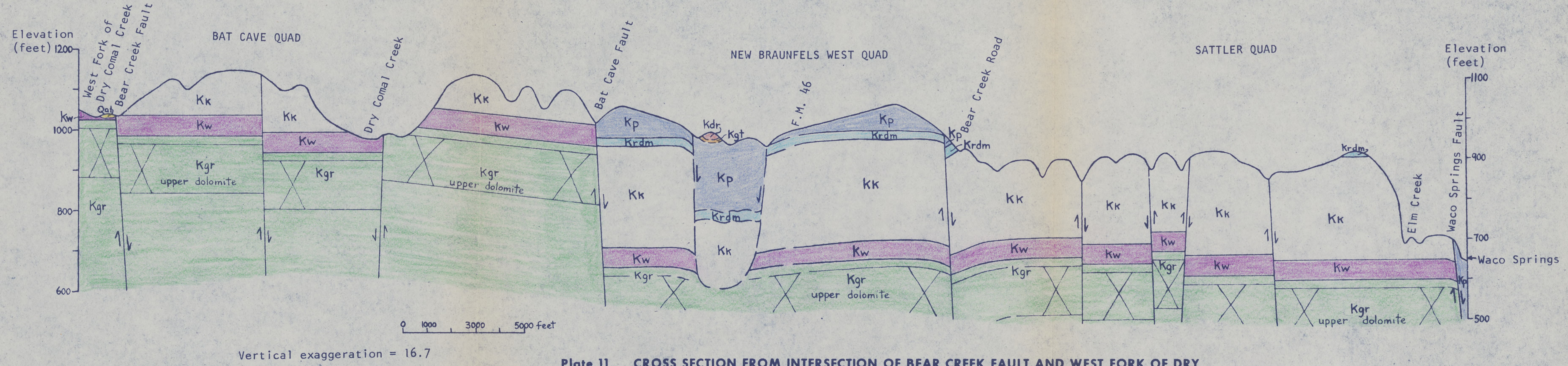


Plate 11 CROSS SECTION FROM INTERSECTION OF BEAR CREEK FAULT AND WEST FORK OF DRY COMAL CREEK ON BAT CAVE QUAD TO WACO SPRINGS ON SATTLER QUAD